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Cognitive and neural mechanisms of bilingual decision making: From visual word processing to decisions under risk

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Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt,

- dass ich die vorliegende Arbeit selbstständig und ohne unerlaubte Hilfe verfasst habe,
- dass ich mich nicht bereits anderwärts um einen Doktorgrad beworben habe
- und keinen Doktorgrad in dem Promotionsfach Psychologie besitze
- und dass ich die zugrunde liegende Promotionsordnung vom 02.12.2008 kenne.

Berlin, den 30.06.2015 Yulia Oganian

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Summary

Bilingual individuals read in their second language (L2) and frequently make decisions based on information perceived in their L2. Compared to monolinguals, visual word recognition in bilinguals bears additional aspects that may also affect later stages of processing. Their integration into neurocognitive models of single word reading and decision making still leaves many open questions. In particular, bilingual word recognition entails the ability to recognize the language membership of a word, and to map letter strings to lexical representations and phonology of the appropriate language, whereby the underlying mapping rules can be different and even contradictory across languages. Furthermore, following these perceptual aspects of word recognition, the perceived information is often used as a basis for higher level, non-perceptual processes, such as decision making under risk. A prominent example for the effects of linguistic framing on decision making is the stronger preference for risky choices when negative outcomes are emphasized than when positive consequences are explicitly stated (the framing effect). The effects of foreign language use on processes influencing the framing effect, most prominently affective processing and cognitive control, has been postulated, but direct evidence for these effects is scarce.

This dissertation's research investigates cognitive and neuronal aspects of bilingual visual word recognition and decision making, using the case of bilingual individuals with native language German (L1) and second language English (L2). Study 1 isolated the effects of word and pseudoword length (i.e. number of letters) on the dynamics of sublexical encoding and lexical access in German and English, using a diffusion model of reaction times (RTs) in lexical decisions. Study 2 investigated whether language membership decisions and naming in a language-ambiguous context are influenced by continuous sublexical (bigram frequencies) and lexical (orthographic neighborhood size) similarity of a letter string to German and English words. This was extended to an investigation of the neuronal correlates of language similarity statistics and language membership representations in Study 3, using functional magnetic resonance imaging (fMRI). Study 4 investigated whether a reduced framing effect during foreign language use is due to reduced affect or increased cognitive control.

Study 1 showed that sublexical encoding of words and pseudowords during lexical decision takes longer for longer stimuli, whereas lexical access is accelerated for words but

slowed for pseudowords. Sublexical length effects in English were larger than previously found in native speakers of English, whereas the effects of length on lexical access in English were similar to those previously reported for English. These findings suggest that sublexical but not lexical processing remains tuned to the orthographic structure of the L1.

In Studies 2 and 3, graded sublexical and lexical language similarities to each of the two languages biased language membership decisions. Moreover, sublexical processing and phonological encoding were faster for letter strings with an L1-typical sublexical structure. fMRI data of Study 3 revealed that brain activity in left ventral occipito-temporal cortex, previously associated with processing of letter strings, was positively correlated with sublexical similarity L1. The level of ambiguity in lexical similarity to L1 and L2 determined activation in bilateral angular gyri, providing direct evidence for language-unselective lexical access in a region previously associated with lexical access in the L1. Brain activations in the left supramarginal gyrus and temporo-parietal junction, previously associated with phonological encoding, were positively correlated with lexical similarity to L1. This finding suggests that phonological representations of the L1 but not L2 are automatically activated during language decisions on visual input. Finally, multivariate fMRI analyses revealed that language membership information is contained in distributed activation patterns throughout the visual word processing network, as well as in additional right parietal areas.

Study 4 showed that in a consistent language setting framing effects are comparable in native and foreign languages and at all foreign language proficiency levels. However, it also revealed that the framing effect is reduced following a language switch, not only into a foreign language but also into the L1. This finding is best interpreted in terms of increased cognitive control following language switching, rather than as altered affective processing during foreign language use, as was claimed in previous studies.

Based on these findings I propose to extend neurocognitive models of bilingual visual word recognition in several aspects. First, sublexical mapping of orthography should prioritize the orthographic structure of the L1. Second, the summed activation propagated from sublexical representations to the lexicon should increase with stimulus length, which would lead to faster lexical access for longer words. Third, lexical representations should be clustered by language, to constitute a basis for language membership information within the core visual word processing network. Fourth, input to language membership representations should stem

from all sublexical and lexical representations, weighted by their typicality for each language. Finally, our findings imply that the input language affects non-linguistic decision processes through a modulation of cognitive control levels and not affective processing. This link needs to be included in integrated models of perceptual linguistic and higher-level processing.

Keywords: bilingualism, word length effect, drift diffusion model, language membership decisions, bigram frequency, orthographic neighborhood size, fMRI, multi-variate pattern analysis

Zusammenfassung

Zweisprachige Individuen können sowohl in ihrer Zweitsprache (L2) lesen, als auch Entscheidungen treffen, die auf in der L2 gelesenen Informationen beruhen. Im Vergleich zur monolingualen visuellen Wortverarbeitung erfordert das Lesen in einer zweiten Sprache zusätzliche Verarbeitungsschritte, die auch nicht-linguistische Kognition beeinflussen können. Die Integration dieser in Modelle der monolingualen Wortverarbeitung und Entscheidungsfindung birgt einige offene Fragen. So erfordert die bilinguale Wortverarbeitung, dass die Sprachzugehörigkeit eines Wortes erkannt wird. Außerdem müssen Buchstabenfolgen lexikalisch und phonologisch in beiden Sprachen verarbeitet werden. Dabei können sich die zugrundeliegenden Abbildungsregeln zwischen den Sprachen unterscheiden und sich sogar gegenseitig widersprechen. Diese perzeptuellen Aspekte der Wortverarbeitung dienen oftmals als Basis für weitere übergeordnete Entscheidungsprozesse, wie z.B. Risikoentscheidungen. Ein wichtiges Beispiel für sprachliche Effekte auf Risikoentscheidungen ist der Framingeffekt. Dieser beschreibt, dass die Bereitschaft ein Risiko einzugehen höher ist, wenn die negativen Konsequenzen von Entscheidungsalternativen explizit beschrieben werden, als wenn positive Konsequenzen betont werden. Der Einfluss des Fremdsprachengebrauchs auf tragende Prozesse des Framingeffekts, insbesondere auf die affektive Verarbeitung und kognitive Kontrolle, wurde zwar desöfteren postuliert, jedoch bis dato nur unzureichend empirisch bestätigt.

Die vorliegende Dissertation untersuchte kognitive und neuronale Aspekte bilingualer visueller Wortverarbeitung und Entscheidungsfindung am Beispiel von Zweisprachigkeit mit Deutsch als Muttersprache (L1) und Englisch als Zweitsprache (L2). In der ersten Studie verglich ich die Effekte von Wort -und Pseudowortlänge auf die sublexikalische Enkodierung und den lexikalischen Zugriff im Deutschen und Englischen. Dazu wurden Reaktionszeiten in einer lexikalischen Entscheidungsaufgabe mit Hilfe eines Diffusionsmodells modelliert. In der zweiten Studie untersuchte ich inwiefern kontinuierliche sublexikalische und lexikalische Ähnlichkeit von Buchstabenfolgen zu deutschen und englischen Wörtern die Sprachzuordnung und Wortbenennung in einem sprachlich ambigen Kontext beeinflusst. In der dritten Studie wurden die neuronalen Korrelate von Sprachähnlichkeit und -zugehörigkeit mithilfe funktioneller Magnetresonanztomographie (fMRT) betrachtet. Schließlich untersuchte ich in

der vierten Studie, ob ein verminderter Framingeffekt in einer Fremdsprache auf reduzierten Affekt oder aber erhöhte kognitive Kontrolle zurückgeführt werden kann.

Studie 1 zeigte, dass die sublexikalische Enkodierung von Wörtern und Pseudowörtern mit zunehmender Länge länger andauert. Hingegen war der lexikalische Zugriff für längere Wortstimuli schneller, für längere Pseudoworte jedoch langsamer. Desweiteren waren sublexikalische Längeneffekte im Englischen größer als im Deutschen. Dieser Befund steht im Gegensatz zu in der Vergangenheit berichteten größeren muttersprachlichen Längeneffekten im Deutschen als in Englischen. Er legt daher nahe, dass die bilinguale sublexikalische Verarbeitung auf die orthographische Struktur der Muttersprache ausgerichtet ist.

In Studien 2 und 3 wurde beobachtet, dass die Sprachzuordnung von Pseudoworten durch ihre sublexikalische und lexikalische Ähnlichkeit zu jeder der Sprachen beeinflusst wird. Zudem wurde sublexikalische und phonologische Enkodierung durch sublexikalische Ähnlichkeit zur L1 beschleunigt. fMRT-Daten aus Studie 3 zeigten eine positive Korrelation zwischen Hirnaktivierungen im linken okzipito-temporalen Kortex, der mit der Verarbeitung von Buchstabenfolgen assoziiert wird, und der sublexikalischen Ähnlichkeit der Stimuli zur L1. Darüber hinaus waren die bilateralen Angulargyri umso aktiver, je ambiger die lexikalische Ähnlichkeit der Stimuli zu beiden Sprachen war. Dieser Befund bietet eine direkte Evidenz für sprachunabhängigen lexikalischen Zugriff in einer Region, die bisher mit lexikalischen Zugriff in monolingualen Studien assoziiert wurde. Aktivierungen im linken supramarginalen Gyrus und im temporo-parietalen Bereich, zwei Regionen denen in phonologischer Enkodierung eine wichtige Rolle zukommt, waren mit der lexikalischen Ähnlichkeit zur L1 positiv korreliert. Dieser Befund legt nahe, dass visuell basierte Sprachentscheidungen eine automatische Aktivierung der L1-Phonologie nach sich ziehen. Aus multivariaten fMRT-Analysen wurde ersichtlich, dass Sprachzugehörigkeit sowohl in verteilten Aktivierungsmustern im gesamten Sprachnetzwerk, als auch in weiteren rechtsparietalen Regionen enkodiert wird.

Studie 4 zeigte, dass der Framingeffekt von der Sprache, in der eine Risikoentscheidung präsentiert wurde, nicht beeinflusst wird, solange die Risikoentscheidung in einen einheitlichen Sprachkontext eingebettet ist. Desweiteren war der Framingeffekt in einer Fremdsprache vom Niveau der Sprachkenntnisse unabhängig. Allerdings reduzierte ein unmittelbarer Sprachwechsel den Framingeffekt, und zwar unabhängig davon, ob von der Muttersprache in eine Fremdsprache oder andersherum gewechselt wurde. Wir interpretieren diesen Befund als

das Ergebnis von erhöhter kognitiver Kontrolle beim Sprachwechsel, und nicht – wie in früheren Studien vorgeschlagen – als modifizierte affektive Verarbeitung beim Gebrauch einer Fremdsprache.

Basierend auf diesen Ergebnissen diskutiere ich eine Erweiterung neurokognitiver Modelle zweisprachiger visueller Wortbearbeitung. In diesem sollte die sublexikalische orthographische Enkodierung die Struktur der L1 priorisieren. Desweiteren sollte die Gesamtaktivierung, die von sublexikalischen Repräsentationen an das Lexikon propagiert wird, mit Wortlänge ansteigen und daher zu einem schnelleren lexikalischen Zugriff führen. Zudem könnten sich lexikalische Repräsentationen nach Sprache gruppieren, um eine Basis für Sprachrepräsentationen innerhalb des Wortverarbeitungsnetzwerkes zu ermöglichen. Außerdem sollten modelltheoretisch alle sublexikalischen und lexikalischen Repräsentationen mit denen der Sprachzugehörigkeit verbunden sein, wobei die Verbindungsstärke mit Sprachähnlichkeit gewichtet werden sollte. Schließlich sollte der Effekt von sprachbedingt erhöhter kognitiver Kontrolle und Entscheidungen unter Risiko in Modellen zur Integration visueller Wortverarbeitung und nicht-linguistischer Entscheidungsprozesse hergestellt werden.

Stichworte: Zweisprachigkeit, Wortlängeneffekte, Diffusionsmodelle, Sprachzugehörigkeit, Bigrammfrequenzen, Orthographische Nachbarschaft, fMRT, multi-variate Analysen

List of Original Publications

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3. Oganian, Y., Conrad, M., Aryani, A., Spalek, K. #, & Heekeren H.R. # (2015). Activation patterns throughout the word processing network of L1-dominant bilinguals reflect language similarity and identity. *Journal of cognitive Neuroscience.* 27(11): 2197-2214.
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4. Oganian, Y.,* Korn, C.W.* & Heekeren H.R. (2016). Language switching – but not foreign language use per se – reduces the framing effect. *Journal of experimental Psychology: Language, Memory, and Cognition.* 42(1): 140-148.
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List of Abbreviations

AoA	Age of acquisition
BF_E	mean English bigram frequency
BF_G	mean German bigram frequency
BIA	bilingual interactive activation
CDP	connectionist dual process model
diffBF	mean bigram frequency difference
diffOLD	difference in orthographic neighborhood size
DRC	dual-route cascade model
fMRI	functional magnetic resonance imaging
GLM	General linear model
IA	interactive activation
L1	Native language
L2	second language
LMI	language membership information
MCMC	Markov-Chain Monte Carlo
MROM	multiple read-out model
OLD_E	English Levenshtein orthographic neighborhood size
OLD_G	German Levenshtein orthographic neighborhood size
RT	reaction times
SLA	second language acquisition

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1. Theoretical and empirical foundations

Language is arguably the most unique human faculty. Its development about 50,000-100,000 years ago was associated with a leap in the organization of brain structures. Their recruitment for a novel ability, to fill sound with abstract meaning, provided humankind with a unique advantage over other species. The invention of written language about 4,000 years ago allowed human societies to develop more complex structures, preserving and passing on information and knowledge. With approximately 6,000 languages spoken in modern human societies around the globe, the ability to communicate with speakers of other languages is a necessary prerequisite for co-existence. Indeed, more than half of the world's population is bilingual, being able to communicate in at least two languages.

In this thesis I investigated cognitive and neuronal mechanisms of bilingual reading, the ability to understand script in two languages, as well as the consequences of reading in a foreign language on the subsequent evaluation of read information.

1.1. Bilingualism

The effects of bilingual experience on the cognitive development and functioning of an individual have been widely discussed, not only in psychology but also in educational science. Moreover, the light in which bilingualism is seen bears wide implication for political decisions (Baker, 2011; Grosjean, 1982). It is widely accepted that knowledge and use of an additional language alter linguistic processing through addition of a second set of lexical, grammatical, and phonological knowledge. Yet, many questions concerning the effects of bilingual experience on language processing remain open (Costa & Sebastián-Gallés, 2014). Not less fascinating are putative effects of bilingualism on various aspects of cognition, e.g. conceptual representations, perception, emotional processing, and decision making, the exploration of which is only in its initial stages (Kroll & de Groot, 2005). Given the high prevalence of bilingualism in human society and its wide-ranging implications, research on any cognitive function cannot be complete without an understanding of its interactions with bilingualism.

1.1.1. Definition of bilingualism

Colloquially, the term “bilingualism” is used for individuals who have acquired two languages early in life or even simultaneously and have a similarly high proficiency in both languages. However, systematic assessment of proficiency shows that equal proficiency in two languages is rarely the case. Rather, most bilinguals have a preference for one language in at least some communicational settings, such as one language at work and the other for interactions with the family (Grosjean, 1982; Kroll & de Groot, 2005). Moreover, most bilinguals have a differentiated history of language acquisition and knowledge. Early acquisition of a second language and the status of a mother tongue do not guarantee high proficiency, whereas a second language acquired in early adolescence following migration can reach a near-native proficiency level (Johnson & Newport, 1989). The cognitive effects of each of these language acquisition histories might be unique and manifold.

To accommodate these distinctions, scientific research of bilingualism typically characterizes the second language status on two dimensions: age of acquisition (AoA) and proficiency level (Birdsong, 2005, 2006). This distinction is supported by research showing that these dimensions do not overlap, as AoA was found to predict proficiency for only some aspects of language learning. For example, AOA predicts proficiency in acquisition of syntax (DeKeyser & Larson-Hall, 2005) and accent (Piske, MacKay, & Flege, 2001; Yeni-Komshian, Flege, & Liu, 2000) in an L2, which can only be acquired to a native-like proficiency level when learned early in life. On the contrary, AoA does not predict proficiency in lexical knowledge and literacy, which can be mastered to a high degree even for languages learned in late adolescence or adulthood (DeKeyser & Larson-Hall, 2005). Findings from electrophysiology and neuroimaging support this distinction (Perani & Abutalebi, 2005; Perani et al., 2003; Wartenburger et al., 2003). For example, Wartenburger and colleagues (2003) found differential effects of AoA on neural networks underlying syntax, but not lexical processing.

Psycholinguistic research incorporates these different aspects of language learning and use by referring with the term ‘bilingualism’ to anyone who is capable of using two languages irrespective of proficiency and AoA. It is thus important to distinguish bilingualism research from research on second language acquisition (SLA). SLA researches the process of becoming a bilingual, whereas bilingualism research is concerned with the changes that the use of a second language, most often at a high level of proficiency, induces in comparison to monolingual processing.

In line with this framework, this chapter first describes the state of the art in cognitive and neuropsychological research on monolingual visual word recognition and decision making under risk. It is then followed by a description of questions that arise in the context of bilingualism.

1.2. Monolingual visual word recognition: data and models

Although babies are not born with the ability to speak and understand speech, they acquire language implicitly and without targeted instruction. This is a central discrepancy from written language, the acquisition of which is far more effortful and requires structured instruction, training, and exercise. However, following an initial period of instruction humans become experts in extracting meaning from script, a process referred to in the literature as visual word recognition. This ability comes along with the specification of a neural and cognitive architecture dedicated to the mapping of letter strings to internal word representations (Dehaene, 2009).

Conceptually, visual word recognition is widely assumed to follow a series of steps through several representational layers (Rastle, 2007). After an initial visual analysis, sublexical units (letter and syllables) are recognized, which in turn activate orthographic and phonological representations of existing word-forms (the lexicon). The process of choosing the correct word-form from all those that bear resemblance to the input is termed lexical access, and is a prerequisite for semantic understanding. Each of these representational layers contains orthographic and phonological representations, with the exception of semantics, which is modality-independent.

Initial evidence for these processing steps comes from neuropsychological research with lesion patients. Using simple reading tasks, two types of lesion patients were identified. Some were able to read regularly spelled pseudowords but not exception words (surface dyslexia, Marshall & Newcombe, 1973). On the other hand, others were able to read real words, albeit with mistakes, but not pseudowords (deep dyslexia, Plaut & Shallice, 1993). This double dissociation led to the development of a model of reading comprised of two distinct reading routes (Coltheart, Masterson, Byng, Prior, & Riddoch, 1983). On the direct – lexical – route, letter strings are directly mapped to the lexicon, whereas on the indirect – sublexical – route, sublexical orthographic representations are mapped to phonological representations. The latter is either based on explicit rules (dual-route cascade model, DRC, Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) or implemented in a distributed neural network (Zorzi, Houghton, & Butterworth, 1998). Another major principle implemented in current models of visual word recognition is the interactive activation principle (IA, McClelland & Rumelhart, 1981). It is motivated by observations that speak in favor of interactive effects between different representational layers, such as words and letters (word superiority effect, Reicher, 1969) and orthographically similar words (effects of orthographic neighborhoods, Grainger, 1990). IA models consist of several levels of representation, each containing local representational nodes of a different linguistic unit (i.e. letters at the orthographic level or word form nodes at the lexical level). Nodes in each representational level activate associated nodes in other representational layers (e.g. the input letter '*b*' excites the words '*book'* , '*back'*, '*basket'*, and '*book'* in turn activates the letters '*b*' '*o*' and '*k'*.), and inhibit competing nodes within the same level (e.g. '*book'* inhibits '*look'* and '*hook'*). In the most recent model of visual word recognition, CDP+ (connectionist dual-process model, Perry, Ziegler, & Zorzi, 2007, Perry, Ziegler, & Zorzi, 2010), sublexical and lexical layers of processing interact according to this principle. Hereby, each layer contains orthographic and phonological representations, which are organized in a dual-process set-up. Computational process models of visual word recognition have the aim of building an architecture that will be able to re-produce reaction time (RT) and response patterns found in healthy subjects in a variety of reading tasks. Figure 2 below provides an overview of the central building blocks and their connections that are shared by all contemporary IA models of visual word recognition. In the following I will describe the two most frequently used tasks in visual word recognition research, as well as the major effects against which models of visual word recognition are tested.

Research on visual word recognition mostly uses two classical tasks, lexical decision and naming. In the lexical decision task, participants have to indicate whether a presented letter string is an existing word or a pseudoword. It is mostly used to investigate the dynamics of lexical access, that is, the activation of orthographic word form representations based on visual input. It should be noted, however, that RTs in the lexical decision task presumably reflect not only the dynamics of lexical activation, but also the duration of preceding processes, most notably visual processing (Nazir, O'Regan, & Jacobs, 1991; O'Regan & Jacobs, 1992), sublexical encoding (Hudson & Bergman, 1985). Moreover, each of these processes can be influenced by decision strategies (Grainger & Jacobs, 1996; Wagenmakers, Ratcliff, Gomez, & McKoon, 2008). In contrast, naming, that is, simple reading of a letter string, taps processes involved in mapping from orthographic representations to phonology. Although dual-process models assume that both reading routes are always activated automatically, this mapping does not depend on lexical access, as regular letter strings can be mapped to phonology via the sublexical route (Zorzi et al., 1998). Overall, the different requirements of the two tasks lead to differential effects of certain psycholinguistic variables in each task. Thus, differences and similarities between the effects of a variable on behavior in the two tasks can inform the understanding of the effects of each variable on different steps in visual word processing (Carreiras, Mechelli, Estévez, & Price, 2007; Carreiras, Perea, & Grainger, 1997; Grainger, 1990).

Word frequency is known to facilitate RTs in lexical decision and in naming. This effect is interpreted as due to higher baseline activation levels of high-frequency lexical units (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; Grainger, 1990; Rastle, 2007), leading to faster activation and thus recognition of matching inputs. Frequency effects for sublexical units are more manifold. Syllable and two-letter pair (bigram) frequencies have an inhibitory effect on lexical decision RTs (Westbury & Buchanan, 2002), but a facilitatory effect on naming RTs (Conrad & Jacobs, 2004; Conrad, Stenneken, & Jacobs, 2006). The former is typically explained as a result of feedback connections from lexical to sublexical units. In contrast, the latter effect provides evidence for speed-up of processing on the sublexical route for more frequent bigrams. Specifically, for high frequency sublexical units feedback connections induce widely spread sublexical activations, which in turn spread lexical activation across a larger number of lexical nodes, hindering identification (Westbury & Buchanan, 2002).

Another variable, which has a strong effect on lexical decision and naming RTs, is the orthographic neighborhood size, referring to the degree of similarity between a letter string and (other) words represented in the lexicon (Andrews, 1997; Yarkoni, Balota, & Yap, 2008). Large orthographic neighborhoods slow down response latencies in lexical decision and in naming. This is interpreted as evidence for lateral inhibition in the lexicon, which increases with the number of co-activated lexical nodes (for an analysis of the effects in naming see Carreiras, Perea, & Grainger, 1997; for a review see Andrews, 1997 and Andrews, 1992).

Further evidence for the interactive nature of visual word processing, in particular top-down feedback, comes from the word superiority effect, first described by Reicher (1969) and Wheeler (1970). They reported that single letters are recognized more accurately, when embedded in a word than in a pseudoword. Similarly, single letters are recognized faster when embedded in a pronounceable non-word letter string that consists of frequent bigrams, than in one that is not pronounceable in the respective language. Feedback processing from semantic representations to the lexical level is also evident in the phenomenon of semantic priming: Faster lexical decision and naming RTs for targets that are preceded by a semantically related prime (Hutchison, 2003; Neely, 1977).

While the aforementioned effects are quite well integrated in IA models, such as CDP+ (Perry et al., 2007), the effect of length on processing times in lexical decision and naming still poses a riddle to models of visual word recognition. A seminal finding is that naming RTs are slower for longer words, and that this effect shows an interaction with lexicality. Specifically, increase of RTs with length is more pronounced for pseudowords than for words (Weekes, 1997). The observation of length effects led to the idea that sublexical processing has to involve some kind of serial processing, during grapheme-to-phoneme mapping (Coltheart et al., 2001), letter-to-grapheme encoding (Perry et al., 2007), or at an earlier stage, during visual processing (O'Regan & Jacobs, 1992). The former two approaches explain the difference between length effects in words and pseudowords through reduced serial processing on the lexical route. In contrast, the visual acuity approach attributes length effects to a stage in processing that is shared between reading routes, such that differences in length effects have to be explained through top-down effects from the lexicon to sublexical representations. Importantly, though, all of these accounts cannot explain length effects in lexical decision, which are robust for pseudowords, but variable for words (Balota et al., 2004). As lexical decisions are based on activation levels in the lexicon, any effects in this task must be explained in terms of processing in the lexical route.

Clarifying this inconsistent pattern is even more challenging in light of recent reports of facilitative effects of length on lexical decisions RTs for real words (Ferrand et al., 2011; New, Ferrand, Pallier, & Brysbaert, 2006). Specifically, these studies found a u-shaped RT function in lexical decision, with acceleration from length 3 to 6 and slower RTs for longer words. A possible reason for this conflicting evidence lies at the core assumption of a single source of length effects. Alternatively, the variation in length effects across tasks and stimulus sets might be due to differential effects of word length on different levels of processing during the lexical decision task. However, no study to date has decomposed the lexical decision task into its sub-processes and tested the effect of word length separately for each sub-process. One promising way to do so is based on computational models of decision making, which will be presented in the next section.

1.3. Computational models of decision making

The lexical decision task belongs to a class of tasks in which participants attribute an input to one of two alternatives, based on perceptual evidence. Such decision tasks are widely used in many areas of research and have been extensively modeled using various computational methods. In the context of this dissertation I will focus on diffusion modeling (Ratcliff & McKoon, 2008). Other approaches include the multiple read-out model (MROM), which is a decision module derived specifically for the lexical decision task (Grainger & Jacobs, 1996), and the leaky accumulator (Dufau, Grainger, & Ziegler, 2012), which is mathematically equivalent to the diffusion model (DM, Bogacz, Brown, Moehlis, Holmes, & Cohen, 2006).

A two-alternative decision process involves mapping from a complex continuous input variable to a binary outcome variable (e.g. from the numbers of grey and white dots to the choice of either ‘more white’ and ‘more grey’). Decision models conceptualize the process of making a decision as accumulating decision-relevant evidence. The evidence is transformed into a decision when a pre-defined criterion is met. The DM provides a general framework for the accumulation of evidence towards one of two decision alternatives (Ratcliff & McKoon, 2008; Voss, Nagler, & Lerche, 2013), for which lexical decisions are one example. Evidence accumulation is modeled using a decision variable which drifts between two decision boundaries until it crosses one of them, in which case a decision is made. The drift process is characterized by four parameters (Figure 1): an initial bias towards one of the alternatives (β); the total time devoted to general, non-decision processes (τ, which include perceptual encoding and motor preparation); the rate of evidence accumulation (ν, which can be thought of as the speed with which a decision boundary is approached); and the distance between decision boundaries (α). In this architecture the upper boundary is located at α, and the lower boundary at 0. The final reaction time is equal to the sum of the decision time and the non-decision time τ. The random variability of the decision process is represented as within-trial variability in the rate of evidence accumulation, which is not fixed in the model but is sampled from a normal distribution with mean ν and variance s. The latter is an intrinsic parameter of the model, and changes in this parameter result in scaling of the other parameters. The joint distribution of total reaction time and the choice of a decision alternative in the diffusion model follows the Wiener distribution with parameters β, τ, ν, and α (see Vandekerckhove, Tuerlinckx, & Lee, 2011, for the exact mathematical form of the distribution). The parameters of the diffusion model for a given data set can be obtained numerically using approaches such as maximum likelihood (Vandekerckhove & Tuerlinckx, 2008) or Bayesian estimation (van Ravenzwaaij & Oberauer, 2009).

In lexical decision, the amount of lexical activation must be compared against a decision threshold signaling the presence of a word that exists in the reader's lexicon. A fully-specified mechanistic implementation of a decision module within the visual word processing framework would require the input of the decision model to be the output of a preceding module that models the visual word recognition process (i.e. one of the models described in the previous section). However, a scaled-down solution is to assume that the amount of evidence is related to measurable properties of the stimulus, such as length, orthographic neighborhood size, or word frequency. While not perfect, this approach is quite reasonable as these variables explain a major part of variance in lexical decision RTs (Yap & Balota, 2009).

A basic question that any model of lexical decision has to cope with is how decisions are made on pseudowords. For existing words the decision can be made based on a lexical match, that is, in the IA framework the existence of a single node that received the most and sufficient excitatory input. There is, however, no match for pseudoword. A popular solution to this problem is the deadline model, according to which a ‘no’ decision is made in lexical decision if no positive decision was made within a certain time frame (Coltheart et al., 2001; Grainger & Jacobs, 1996). However, a major problem with this model is that it does not allow for faster ‘no’ decisions than ‘yes’ decisions. The diffusion model provides a solution to this problem by allowing a decision to be made based on fluctuations in the amount of evidence during the decision process (Wagenmakers et al., 2008).

The main advantage of the diffusion model over analyzing means of raw RTs is that the model parameters putatively reflect specific, cognitively meaningful, stages in the decision process. The drift rate (ν) conceptualizes the core of the decision process, namely the rate of evidence accumulation, which increases with the amount of decision-relevant information in the stimulus. The non-decision time (τ) is associated with stimulus encoding and motor preparation. Importantly, for decisions with little variance in motor preparation (i.e. when only a simple button press is required), increases in non-decision time can be attributed to more effortful stimulus encoding (Ratcliff & Smith, 2010).

The diffusion model has provided valuable insights into decision processes at a cognitive and neural level, for example in visual perceptual decision (Gold & Heekeren, 2013; Huk & Shadlen, 2005), memory retrieval (Ratcliff, 1978), and in the effects of aging in different domains (Ratcliff, Thapar, Gomez, & McKoon, 2004; Ratcliff, Thapar, & McKoon, 2004). In lexical decision, the diffusion model successfully explained several effects of psycholinguistic, contextual and inter-individual factors (Ratcliff, Gomez, & McKoon, 2004; Wagenmakers et al., 2008) through modulation of single model parameters. Wagenmakers et al. (2008) showed that the diffusion model accounts for responses to pseudowords that are faster than responses to words, through a strategy-dependent boundary shift. Ratcliff, Gomez & McKoon (2004) demonstrated that the effects of word frequency on lexical decision RTs selectively map to an increase in drift rates. Ratcliff and colleagues (2004) found that slowing of responses with age is due to changes in the decision boundary and not a reduction in rate of evidence accumulation. These findings provide evidence for isolated effects of behavioral factors on the diffusion model parameters and corroborate their mapping to distinct cognitive processes. In the context of length effects on lexical decision, the diffusion model might provide novel insights by mapping of length effects separately for drift rates, putatively reflecting lexical activation, and for non-decision times, putatively reflecting sublexical encoding. I followed this approach in Study 1.

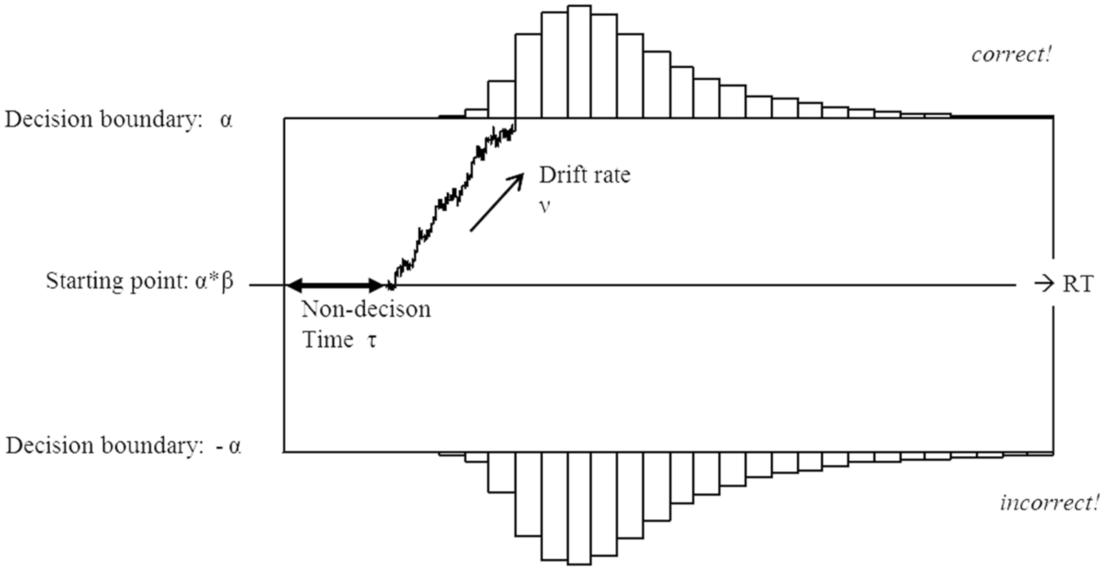

Figure 1: Schematic illustration of the diffusion model.

The decision is made based on evidence accumulated with a drift rate ν. The average drift rate is positive on trials with the upper boundary being the correct response, and negative on trials with the lower boundary being the correct response. Non-decision processes, such as stimulus encoding and motor preparation are represented by the non-decision time τ. The decision is made once the amount of evidence exceeds one of the pre-defined decision boundaries α or 0. An unbiased decision process starts at the point $\frac{\alpha}{2}$, that is a bias β of 0.5. A value of β larger than 0.5 indicates a bias towards the upper decision boundary, while a value of β smaller than 0.5 indicates a bias towards the lower decision boundary.

1.4. The neural network underlying visual word processing

As language is a uniquely human faculty, investigation of the neural mechanisms of linguistic processing was limited to lesion studies until the advance of neuroimaging methods. Today positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) allow for a spatial localization of neural networks underlying spoken and written language (for a review see Price, 2012) in healthy individuals. Moreover, development of electroencephalography (EEG) at the beginning of the 20th century and its application to basic psycholinguistic research from the 1950s on allowed for an analysis of the time course of linguistic processing (Kutas, 1993; Sereno & Rayner, 2003). Importantly, the use of neuroimaging methods enables research on more naturalistic tasks, such as passive reading, as the dependent variable measures (Blood oxygenation level dependent [BOLD] signal in fMRI, or scalp potential in EEG) do not require an explicit behavioral response. In the following, I will discuss the neuroimaging evidence for the localization of neural networks dedicated to language processing. I will also discuss the mapping between identified brain networks and sub-processes of cognitive models of visual word recognition, such as functionally separate neuronal representations of orthographic and phonological units at sublexical and lexical levels (Carreiras, Baayen, Perea, & Frost, 2014).

Early evidence for a neural structure dedicated to orthographic processing comes from patients who suffered an acquired reading disability following brain damage to the left occipital lobe (Dehaene & Cohen, 2011; Hillis & Caramazza, 1995). Neuroimaging studies confined sublexical processing of script to a region in left ventral occipito-temporal lobe, in proximity of the fusiform face area, termed the visual word form area (VWFA, Cohen et al., 2000, 2002, for alternative interpretations see Devlin, Jamison, Gonnerman, & Matthews, 2006; Price & Devlin, 2003; Twomey, Kawabata Duncan, Price, & Devlin, 2011). The VWFA is preferentially active when participants are viewing letter strings but not in response to other complex objects, such as faces or houses, or strings of letter-like symbols (Hasson, Levy, Behrmann, Hendler, & Malach, 2002). Moreover, its activation when individuals view pseudowords increases with pseudowords' similarity to words (such as *pksfsr* vs. *pakser*, Binder, Medler, Westbury, Liebenthal, & Buchanan, 2006; Vinckier et al., 2007). It should be noted that while the VWFA is left-hemispheric and similar lesions to homologous righthemispheric regions do not impair reading, some smaller regions in the right hemisphere also exhibit sensitivity to letter strings (Hasson et al., 2002). A long-standing debate in research on neural processing of letter strings is whether the VWFA encodes letters or orthographic word words (Nestor, Behrmann, & Plaut, 2013). Evidence exists for both possibilities, with a likely solution to the debate being a functional subdivision, according to which the posterior part encodes sublexical orthography and the anterior part encodes orthographic word-forms (Thesen et al., 2012).

The neural correlates of lexical access are typically investigated using a comparison between different types of stimuli in naming and lexical decision. For example, activation in the angular gyrus increases when naming words, which relies on lexical access, compared to pictures, which does not (Menard, Kosslyn, Thompson, Alpert, & Rauch, 1996; Price, 2012). In lexical decision, the angular gyrus is more active during decisions on words with fewer orthographic neighbors (Binder et al., 2003). These findings are interpreted as reflecting the involvement of the left angular gyrus in lexical access, with higher activation levels reflecting more effortful lexical access. Furthermore, increased reliance on phonological processing, e.g. in pseudoword as compared to word naming, is associated with activation of the supramarginal gyrus and the posterior part of the superior temporal gyrus (Mechelli, Gorno-Tempini, & Price, 2003; Simos et al., 2002; Xu et al., 2001). Finally, semantic processing, as required in semantic categorization but not lexical decision, leads to increased activation of medial temporal regions (Carreiras et al., 2014).

In summary, the neural network involved in single word reading is mostly left-lateralized. It includes the visual word form area in ventral temporo-occipital cortex for sublexical orthographic processing, the angular gyrus and possible anterior parts of vOT for lexical processing, supra-marginal and superior temporal regions for phonological processing, and medial temporal lobes for semantic processing.

A central issue in research on the neural basis of bilingual visual word recognition is whether the same or additional brain regions are recruited for reading in the L2. To approach this question, I first present cognitive models of bilingual visual word recognition, and then review neuroimaging data on the organization of two languages in the bilingual brain.

1.5. Visual word recognition in bilingualism

What are the changes that the visual word recognition system undergoes during acquisition of literacy in a second language? Two major questions must be answered for a comprehensive account of bilingual visual word recognition. First, it is essential to outline the overlap and distinction in representations and mapping principles between the native language (L1) and the second language (L2). Second, the system has to include a qualitatively novel level of information, namely the language membership of representations at each level. I will discuss each of these aspects in turn.

The incorporation of L2 representations in the visual word processing system could follow two fundamentally different approaches (Costa, La Heij, & Navarrete, 2006). First, a second, distinct set of representations could be created, with no interaction between representations of different languages at any levels of processing (Gerard & Scarborough, 1989; Macnamara & Kushnir, 1971). This approach is often described as ‘two monolingual systems in one brain’. Alternatively, L2 representations could be incorporated into the native language network (Dijkstra & van Heuven, 2002; Grainger & Beauvillain, 1987; Grainger & Dijkstra, 1992). According to this approach, the interactive nature of the monolingual visual word recognition system would be extended to include L2 representations. In this case mutual inhibition within each single processing level and excitation across levels would exist between and across languages, guided by the same principles as in the monolingual case. The two alternatives can be exemplified on the case of lexical representations of the L2. According to the first approach, a second lexicon is built up that is completely separated from the L1 lexicon. According to the second approach, however, representations of L2 word forms are integrated into the native language lexicon, with lateral connections to similar word forms from the L1, and input from the same sublexical nodes as L1 lexical entries. A related question is whether bottom-up activation spreads across appropriate lexical items of both languages or whether lexical access can be restricted to one language only, the latter hypothesis termed language-nonselective lexical access.

Language-selective lexical access and a separation of the lexica are most plausible in the case of two languages which bear no resemblance to each other on the orthographic level, such as Chinese and English. However, the critical test for this hypothesis is the existence of cross-linguistic interactions in bilinguals of orthographically similar languages, such as Dutch, English, French, or German. One approach for testing cross-linguistic interactions is using words that share some representational aspect across languages, such as cognates, homographs, and homophones (Lemhöfer & Dijkstra, 2004): C*ognates* share form and meaning across languages (e.g. *LAND* or *RING* are examples of German-English cognates), homographs share orthographic form but not meaning (*KIND* and *GIFT* are examples of German-English homographs), and homophones share phonology, but not necessarily orthography (e.g. *GARDEN* and *GARTEN*). If cognitive representations in bilinguals' two languages are completely separated, the processing of such words should not differ between monolingual and bilingual speakers. A shared representational system, however, suggests that processing in one language would be inferred with by activation of the other language. This question has been investigated using lexical decision, naming, and priming paradigms.

A large body of research found that in L1 and L2 lexical decisions on cognates are faster than lexical decisions on non-cognates, and this is even true if the experiment is completely monolingual (Caramazza & Brones, 1979; Costa, Caramazza, & Sebastian-Galles, 2000). This facilitation is stronger in bilinguals' non-dominant language, but exists also in the dominant language, supporting the idea that orthographic representations of cognates are shared, or at least closely connected, between languages. Similarly, it was found that processing of inter-lingual homographs and homophones is affected by their meaning (in semantic priming experiments, Dijkstra, Miwa, Brummelhuis, Sappelli, & Baayen, 2010; Kerkhofs, Dijkstra, Chwilla, & De Bruijn, 2006) and frequency (in lexical decision, Dijkstra, Grainger, & van Heuven, 1999; Lemhöfer & Dijkstra, 2004) in the non-target language. These findings suggest that orthographic word-form representations of cognates and homographs are shared between languages. Recently, this research was extended to languages with distinct orthographies. Wu & Thierry (2010) found that phonological overlap between Chinese and English words leads to phonological priming in an English naming experiment. In summary, these findings suggest that representations that are similar between languages are also shared, or at least co-activated, in the visual word processing system.

While these studies focused on words that are shared between languages at some representational level, this is not the case for the majority of words. For language-unique words, however, the question is whether between-language orthographic neighbors, i.e.

orthographically similar word-forms, are activated during visual word recognition, as is the case for within-language neighbors (see section 1.2 on visual word processing). For example, the English words *book* and *look* differ only in one letter, but this is also true for the English word *book* and the German word *bock*. As described previously, orthographic neighborhood size modulated reaction times in monolinguals' lexical decision (Andrews, 1997). If activation of word form representations is based on orthographic similarity not only within but also across languages, similar effects should be present for between-language orthographic neighborhoods. Indeed, it was found that large between-language orthographic neighborhoods lead to faster lexical decisions, supporting the notion of language-nonselective lexical access (Midgley, Holcomb, van Heuven, & Grainger, 2008; van Heuven, Dijkstra, & Grainger, 1998). The finding that lexical representations of both languages are integrated into a shared interactive network raises the possibility that the same holds for sublexical representations. Indeed, syllable and rhyme frequencies, two sublexical variables, also affect naming speed across languages (Conrad, Alvarez, Afonso, & Jacobs, 2014), suggesting that orthographic representations are shared across languages.

The above findings provide compelling evidence for language-nonspecific sublexical and lexical representations and language-independent processing. Nevertheless, bilinguals are highly aware of the language affiliation of single words, thus opening up the question of how the language identity of word-forms is represented. Moreover, the knowledge of the input language can alter processing to be more efficient, by limiting lexical access to one language (Libben & Titone, 2009; Schulpen, Dijkstra, Schriefers, & Hasper, 2003; Titone, Libben, Mercier, Whitford, & Pivneva, 2011; Yiu, Pitts, & Canseco-Gonzalez, 2015). This can be particularly useful in mixed-language scenarios, which are prevalent in spoken communication among bilinguals, but can also happen in informal written communication.

Grainger and Dijkstra (1992) discussed two possible implementations of language identity information. One was the concept of 'language tags' attached to each word and active immediately with the word-form representation in the lexicon. The other was the concept of an additional representational level – 'language nodes' – with abstract representations of language identity that are connected to all word-forms of a language. Language nodes would receive excitatory input from activation of word-forms from the respective language and inhibit each other. An important difference between these two concepts is in the time course of activation.

While language tags would be active immediately with word form representations, language nodes would reach an activation peak somewhat later, as they would only receive activation propagated from word representations. Grainger and Dijkstra (1992) contrasted these hypotheses by comparing RTs in lexical decision and a language decision task. They assumed that RTs should not differ between tasks according to the language tag account, whereas language decision should be slower according to the language node account. They found that the latter was the case, establishing language nodes as a major component of models of bilingual visual word recognition (Dijkstra & van Heuven, 2002). Although initially Grainger and Dijkstra suggested that language nodes were connected to word representations only, recent results suggest that they can also be activated by language-specific sublexical representations (Casaponsa, Carreiras, & Duñabeitia, 2014; Vaid & Frenck-Mestre, 2002; van Kesteren, Dijkstra, & de Smedt, 2012). Van Kesteren and colleagues (2012) found that Norwegian-English bilinguals made faster language decisions on Norwegian words that contained letters that exist in Norwegian only, such as Ø. Similarly, Vaid and Frenck-Mestre (2002) showed that French-English bilinguals made faster language decisions for words that contained bigrams that exist in French but not in English (e.g. *oe*), coined *orthographic language markers*, even though each single letter of the marker bigrams exists in both languages.

Following these findings, van Kesteren et al. (2012) suggested that models of bilingual visual word recognition should include two sets of language nodes. Sublexical language nodes should receive input from language-specific sublexical representations, such as orthographic markers and single language-specific letters, lexical language nodes from all words that are not unique to one of the languages. They proposed an updated version of the bilingual interactive activation model plus (BIA+, Dijkstra & van Heuven, 2002), which is based on the interactive activation model of monolingual visual word recognition, but features shared lexical and sublexical representations, as well as sublexical and lexical language nodes (see Figure 2).

The evidence reviewed so far focuses exclusively on language identity recognition based on language-unique representations, such as language membership of lexical word forms and orthographic markers, which exist in one language only. These representations can be considered dichotomic language membership cues, as they provide definite language membership information and should be connected to language nodes of only one language.

However, monolingual and bilingual visual word processing is also influenced by continuous linguistic information, such as bigram frequencies and orthographic neighborhood sizes. Thus the question arises whether bilinguals can use sublexical frequencies and lexical orthographic neighborhood sizes in each of the languages to estimate the language identity of stimuli. That is, differences in frequencies of occurrence between languages could be used as cues to determine language membership. This would only be possible if bilinguals were able to assess sublexical (i.e., bigram frequencies) as well as lexical (i.e., orthographic neighborhood sizes) statistics separately for L1 and L2, and if language nodes were to receive activation from language-nonspecific sublexical units and partially activated lexical units. Alternatively, sublexical frequency information might be summarized across languages, in which case statistical information could not be used in language membership decisions. An investigation of the putative effects of fine-grained sublexical and lexical statistical information would provide important insights into the principles governing the internal structure of first and second language representations at sublexical and lexical levels, and is the topic of Studies 2 and 3.

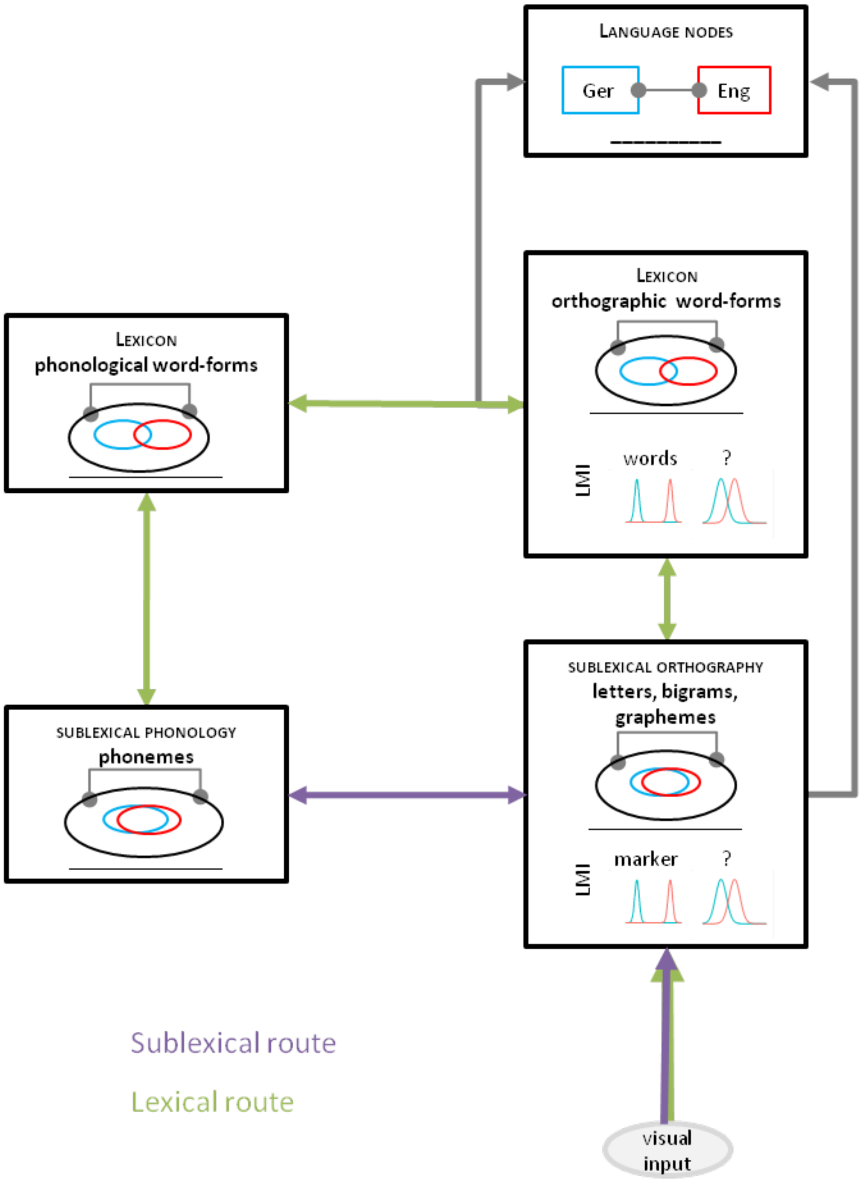

Figure 2: A schematic illustration of the connectionist dual-process model (CDP) and the bilingual interactive activation model (BIA+).

All representational layers except for language nodes exist in both models. In the CDP model, representations at each level stem from one language, whereas in BIA+ representations from both languages are integrated in one IA network. Language nodes and their connections to sublexical and lexical representations are based on BIA+. Blue and red ovals schematically illustrate the amount of shared representations for English and German. For example, most sublexical units are shared between languages, whereas most word-forms belong to one language only. Continuous language membership information (LMI) is also not stipulated in the model. Arrows indicate excitation, and circular edges inhibition.

1.6. Orthographic consistency and length effects

The evidence reviewed so far speaks strongly in favor of language-nonselective processing of letter strings. However, the mapping of orthographic to phonemic representations is guided by conversion rules, which could differ and often even contradict each other between languages (e.g. the different pronunciations of the word ‘stop’ in English and German). These differences and their behavioral instantiations have been thoroughly researched in German and English, which differ in the complexity of grapheme to phoneme conversion rules (Frith, Wimmer, & Landerl, 2009; Ziegler & Goswami, 2005, 2006).

English has a deep orthography, characterized by ambiguity in the relation between single letters and corresponding sounds. For example, the letter o is pronounced differently in through and board. On the other hand, in German, which is an example of a shallow orthography language, both letters are always mapped to the same sound. In shallow orthographies a single grapheme consists of fewer letters than in deep orthographies, such that mapping from orthography to phonology can be based on small chunks of letters or even single letters. In contrast, deep orthographies require the correct chunking of an input into graphemes before a phonological code can be assembled. With their influential 'grain size' theory, Ziegler and Goswami (2005) suggested that these differences lead to differences in reading strategies that reflect the demands of the respective orthography. They proposed that readers of German parse a letter string based on small letter groups, whereas readers of English learn to perceive a larger letter chunk at a time. Importantly, Goswami and colleagues (Goswami, Ziegler, Dalton, & Schneider, 2003) found that switching between these different strategies is only possible under specific conditions.

A seminal finding in favor of the grain size theory is the reduced effect of length in English as compared to German (Ziegler, Perry, Jacobs, & Braun, 2001). As length effects are commonly interpreted as resulting from serial letter-to-grapheme conversion, the grain size theory provides a compelling explanation for the steeper increase in naming times with word length in deep orthographies, such as English, than in shallow orthographies, such as German. Specifically, Ziegler et al. (2001) suggested that the grapheme-to-phoneme conversion is faster when each grapheme contains more letters, as in English. A question that was not investigated is whether bilinguals adjust their parsing strategies to whether they are reading in a shallow or deep orthography. The grain size theory makes no predictions concerning this issue. Specifically, it is an open question whether native readers of shallow orthographies are able to adjust their grapheme-to-phoneme conversion strategies when reading in a second, deep orthography. I investigated this question in Study 1, using the length effect as a measure of grain sizes used in grapheme-to-phoneme encoding.

1.7. Neural processing of a second language

One of the most intriguing questions in research on the neurobiology of language is how a second language is organized in the brain, and whether it is integrated in neural networks that process the native language, as suggested by findings from cognitive psychology. The first fMRI studies of second language processing already found that the same neural network previously identified for reading and listening to the native language, was also active for the same tasks in a foreign language. This was true in particular for occipital activations in the VWFA and parietal activations in the angular and supramarginal gyri (Abutalebi, 2008; Consonni et al., 2013; Klein et al., 2006). At low proficiency levels additional brain regions are recruited, most prominently brain regions implicated in domain-general cognitive control (such as the caudate and the anterior cingulated (Crinion et al., 2006). However, these activations are reduced at higher proficiency levels (Abutalebi et al., 2012; Perani & Abutalebi, 2005). Importantly though, little is known about how psycholinguistic variables that are known to affect processing of L1 and L2, such as orthographic neighborhood size or bigram frequencies, affect activation of the involved brain regions for a second language. For example, the sensitivity of the VWFA to native language bigram frequencies is well documented (Binder et al., 2006; Vinckier et al., 2007), but its sensitivity to L2 bigram frequency has not been investigated so far. Similarly, it is not clear how lexical L2 structure, such as orthographic similarity, is integrated into that network.

Another central question pertains to the neural representation of language identity itself. While cognitive models suggest that language identity of words is represented in a separate layer of visual word recognition system (such as in the BIA+ model, van Kesteren et al., 2012), no study to date has investigated the neuronal mechanisms of this ability. Two kinds of neural representations for language identity are theoretically plausible. According to one, even though large-scale networks seem to be shared between languages, activation patterns of neuronal assemblies in this network might encode language membership. Computational models suggest that this approach is computationally feasible (Shook & Marian, 2013), but it has not been tested experimentally. Alternatively, language identity might be represented in dedicated neural networks, possibly outside the classical language processing areas. This latter alternative most closely resembles the cognitive architecture of the BIA+ model. These questions will be addressed in Study 3.

1.8. Non-linguistic decision making and bilingualism

> *"If you talk to a man in a language he understands, that goes to his head. If you talk to him in his own language, that goes to his heart."* Nelson Mandela

It is colloquially believed that bilingualism affects mental abilities outside of classical linguistic processing. As such, anecdotal evidence of the effects of foreign language use on personality, decision making, and interpersonal communication, suggests that persons turn more outgoing when switching to a different language (e.g. Germans speaking Spanish, Veltkamp, Recio, Jacobs, & Conrad, 2012), or that bilinguals feel less emotional in their second language (Pavlenko, 2012). However, only recently has the interaction of bilingualism and non-linguistic cognition moved into the focus of psychology (Costa & Sebastián-Gallés, 2014). Putative effects of bilingualism have been reported for two major cognitive functions: cognitive control (Bialystok, Craik, & Freedman, 2007; Garbin et al., 2010; Wu & Thierry, 2013) and affective processing (Pavlenko, 2012).

Improved executive function and cognitive control ability were reported following long-term use of a foreign language (Bialystok et al., 2007; Bialystok, Craik, & Luk, 2012). In a seminal work, Bialystok and colleagues reported later Alzheimer onset in bilinguals as compared to monolinguals (Bialystok et al., 2007; Bialystok, Craik, & Freedman, 2010). This finding was followed by studies reporting a bilingual advantage on a range of cognitive control tasks, such as the flanker task (Bialystok & Depape, 2009; Costa, Hernández, & Sebastián-Gallés, 2008). Recently, Wu and Thierry (2013) reported that Chinese-English bilinguals performed better in a flanker task, when Chinese and English words were switched between trials than when words of one language only were inserted. The putative mechanism that was suggested to underlie all these findings is enhancement of cognitive control abilities following frequent language switching. Indeed, previous research has shown that voluntary switching between languages requires the involvement of general cognitive control to suppress the non-target language (Meuter & Allport, 1999; Price, Green, & von Studnitz, 1999). Moreover, language switching was also associated with activation in brain regions associated with cognitive control, such as the caudate (Crinion et al., 2006) and the anterior cingulate cortex (Abutalebi et al., 2007). It was suggested that frequent language switching, as is typical for bilingual individuals, trains cognitive control abilities, leading to better performance on related non-linguistic tasks. It should be noted, however, that recent evidence bids caution with the notion of a bilingual advantage in non-linguistic cognitive control (Bialystok, Kroll, Green, Macwhinney, & Craik, 2015; de Bruin, Treccani, & Della Sala, 2014, 2015; Duñabeitia & Carreiras, 2015), suggesting that advantages might be less general than previously suggested, possibly confined to certain populations and tasks.

Affective processing in bilinguals has been investigated using affective priming and direct affect ratings (Altarriba & Canary, 2004; Colbeck & Bowers, 2012; Opitz & Degner, 2012). Two main differences were found between processing of affective linguistic stimuli in native and foreign language. First, the magnitude of affective priming in L2 is smaller at low proficiency levels and in participants who rarely used their L2 (Opitz & Degner, 2012), but approached native language magnitudes at high proficiency levels and following L2 immersion. Second, affective processing in L2 appears to happen on a slower timescale (Conrad, Recio, & Jacobs, 2011; Opitz & Degner, 2012). These findings are thought to be due to differences between L1 and L2 lexical representations, but also due to altered cognitive control demands during L2 use. At the linguistic level, it is assumed that the link between lexico-semantic representations and affect in L2 is weaker than in L1, due to lower frequency of word use in L2 (Opitz & Degner, 2012). In terms of the cognitive control account, it has also been suggested that the use of a foreign language is less automatic, which leads to increased cognitive load (Pavlenko, 2012). Either of these two presumably leads to reduction in automatic processes during L2 use, in particular a reduction of automatic affective processing.

An important setting where cognitive control and affective processing interact is during decision making under risk (De Martino, Kumaran, Seymour, & Dolan, 2006; De Neys & Bonnefon, 2013; Kahneman, 2003; Stanovich & West, 2008; Whitney, Rinehart, & Hinson, 2008). Humans typically exhibit decision making behavior that does not follow rational (i.e. economically most beneficial) assessments of risk and benefit. Instead, they exhibit an individually varying aversion against losses and risks, leading to an underestimation of potential benefits and an overestimation of potential risks (Mohr, Li, & Heekeren, 2010; Tom, Fox, Trepel, & Poldrack, 2007). Another bias typically exhibited by individuals is the tendency to adhere to moral principles, such as not to cause direct damage to others, which leads to non-utilitaristic behavior in tasks that involve human losses or amoral behavior. Such behaviors are often explained in terms of emotional processing as opposed to rational reasoning (Greene & Haidt, 2002).

A well-established decision bias is the framing effect, in which the choice between a guaranteed, sure outcome and a risky choice alternative of equal expected value[1] depends on the phrasing of the problem description. Specifically, participants are more risk averse when a task is formulated in terms of expected gain than in terms of expected losses (Kahneman, 2003; Tversky & Kahneman, 1981, see also Table 3 in methods section for an example). Recently, Keysar and colleagues (Keysar, Hayakawa, & An, 2012) claimed that framing effects are reduced when the framing task is presented to bilingual individuals in their foreign (weaker) language. They interpreted their finding along the lines of reduced emotional processing in a foreign language, leading to more rational processing. This result inspired a series of studies on the effects of foreign language use on different domains of decision making, such as utilitaristic behavior, moral transgressions, and others (Costa, Foucart, Arnon, Aparici, & Apesteguia, 2014; Costa, Foucart, Hayakawa, et al., 2014; Geipel, Hadjichristidis, & Surian, 2015; Hadjichristidis, Geipel, & Savadori, 2015).

However, as the framing effect involves control processes as well as affective processing, it is in fact also possible that foreign language effects on framing resulted from altered cognitive control and not from increase in emotional distance during foreign language use. Two distinct hypotheses can be derived from these alternatives. Emotional involvement during foreign language use should increase with proficiency and foreign language experience, whereas cognitive control involvement is not dependent on proficiency. On the other hand, as discussed above, cognitive control is particularly enhanced during language switching. An exploration of such theory-driven hypotheses is necessary to understand the link between

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[1] Defined as the mean of all possible outcomes weighted by their respective likelihoods.

ilingualism and decision making at a mechanistic and not only purely phenomenological level, and is the topic of Study 4.

2. Research objectives and hypotheses

This thesis investigates changes to the visual word processing system that are associated with knowledge of second language and related linguistic (perceptual) decision processes in bilinguals. Moreover, it asks how second language use interacts with non-linguistic decisions making. In four studies my co-authors and I addressed the following research questions:

1. Is seriality in sublexical processing, as indicated by length effects, confined to the sublexical route or is sublexical processing as required for lexical access also serial? (Study 1)
2. What are the effects of the orthographic consistency of bilinguals' L1 and L2 on grapheme-to-phoneme mapping in each of the languages and how do they compare to monolinguals of the respective languages? (Study 1)
3. How is language membership information represented in the bilingual visual word recognition system, and are bilinguals' decisions on the language identity of letter strings modulated by continuous sublexical and lexical language similarities? (Study 2)
4. How are sublexical and lexical language similarity statistics represented in the neural network underlying visual word processing? (Study 3)
5. Does the neural network underlying visual word processing contain language identity information, and if so what parts of it? (Study 3)
6. How does the language in which information is presented affect non-linguistic decision making, such as decisions under risk and how are these effects altered by language switching (Study 4)?

The first question addresses the long-standing conjecture that sublexical processing in the lexical reading route, which is involved in the lexical decision task, has no serial aspects. We attempted to answer this question in Study 1 by decomposing the effect of length, a marker of serial processing, on lexical decision response latencies using the diffusion model. We hypothesized that sublexical effects of length would be mapped onto the non-decision parameter of the diffusion model. If serial processing occurs for words and not only for pseudowords, non-decision times would increase with length for both types of stimuli. As this was the first study to investigate the effects of length on the rate of evidence accumulation, we had no specific predictions although based on models such as CDP+ we expected no effect of length. To answer our second question participants in study 1 performed the lexical decision task not only in their native language German but also in their second language English. We were interested to see whether we would see a stronger increase with length in participants' native language German than in English, as found in native speakers of German and English.

My third research question focuses on a process that is unique to multilinguals, namely language membership decisions. In Studies 2 and 3 we examined how different continuous statistical variables at sublexical (i.e. bigram frequencies) and lexical (i.e. orthographic neighborhood sizes) levels in bilinguals' first and second language can be employed to identify input language, a question that has not been addressed previously. In Study 2 we tested two further aspects of language membership decisions. First, we investigated how the effect of continuous language similarity statistics changes when deterministic sublexical cues (i.e., orthographic markers), are contained in the stimulus. Second, we compared the effects of continuous language similarity statistics in language membership decisions to their effects in a naming task, where phonological output in one of the languages is required.

The third and fourth research questions pertain to the neural networks underlying the processing of continuous language-similarity statistics and their involvement in explicit language decisions. These questions were investigated using functional magnetic resonance imaging in Study 3. Study 3 employed the same language decision task as Study 2, but focused on continuous language similarity statistics only. We tested whether activation in the visual word processing network was correlated with statistical language similarity to L1 and L2 separately, at sublexical and lexical levels. Moreover, we used multivariate decoding methods to test whether patterns of activation across neural populations reflect participants' language decisions.

Finally, the last question expands the investigation to the interaction of linguistic and non-linguistic processing in decision-making under risk. The aim of this project was to directly contrast an account of foreign language effects based on emotional distance and an account based on increase in cognitive control. We tested this in Study 4 in two experiments with the framing effect. In the first experiment we tested the hypothesis that emotional attachment should increase with experience, and thus proficiency, with the second language. In the second experiment we employed a design in which bilinguals answered the framing problem either in a consistent language context or following a language switch, testing the hypothesis that language switching would increase cognitive control, which in turn would lead to a reduced framing effect.

3. Methodology

3.1. Experimental samples

Studies 1 – 3 of this dissertation employed methodologies that required repeated-measures designs and accurate measurements of response times. Thus, they were conducted in the laboratory, with each experiment featuring 20-30 participants. Study 4 employed a task in which participants' choices but not reaction times were recorded. Such tasks require between-subject designs with accordingly large numbers of participants. Thus, to make data collection feasible, these experiments were conducted online and in classroom settings.

3.1.1. Studies 1 – 3

A total of 106 German native-speaking university students with a high proficiency in their second language English participated in studies 1 – 3. All participants studied English in high school as their first foreign language, and had spent at least 9 consecutive months living in an English-speaking foreign country (GB, USA, English-speaking Canada, Australia, or New Zealand). Participants' English proficiency was assessed with a language history questionnaire, which they completed online prior to the experiment (adapted from Li, Sepanski, & Zhao, 2006). The results of the language history questionnaire were used to ensure that participants had no other native language and that they estimated their English proficiency as above 4 on a 1-7 Likert scale, separately for reading, writing, speaking, and listening. Moreover they provided a self- assessment of the strength of their English accent. At the end of the experiment, two additional proficiency tests were used to assess participants' proficiency in German and English. First, overall proficiency was assessed with the LEXTALE tests in English and German (Lemhöfer & Broersma, 2011), which evaluate knowledge of vocabulary and morphological structure through specifically designed lexical decision tasks. Performance in this task is evaluated in terms of percentage correct. Word and pseudoword reading speed was tested with the reading and phonological decoding subtests of the TOWRE (Torgesen & Rashotte, 1999) for English and the word and pseudoword reading subtests of the SLRT-II test (Moll & Landerl, 2010) for German. Both tests assess the reading rate (words/min) in single-item naming of words and pseudowords (PW). A summary of participants' language profiles for Studies 1 – 3 is presented in Table1. In all studies and for all proficiency tests, performance in English was below the performance in German. However, all participants displayed an overall high level of performance in both languages.

Participants were right-handed, had normal or corrected-to-normal vision, and did not suffer from a reading disability or other learning disorders. They were recruited through advertisements on campus and in dedicated mailing lists. All participants completed an informed consent form prior to beginning the experiment. They were reimbursed either monetarily or with course credit.

3.1.2. Study 4

All participants in Study 4 were native speakers of German with foreign languages English or French (Experiment 1). They completed a demographic questionnaire and a short language history questionnaire (a short version of the questionnaire used in Studies 1 – 3) at the end of the experiments. Participants' data were analyzed if they fulfilled the following criteria: (1) German was their only mother tongue; (2) their current residence was a German-speaking country; (3) they were between 18 and 60 years old; (4) they had no prior knowledge of the framing effect. Additionally, participants in the online versions of the experiments were excluded if their reaction times in the Asian disease task deviated more than 2 standard deviations (SD) from the group mean. In Experiment 1, participants who completed the survey in an FL (English or French) were assigned to the low-proficiency group if their self-reported proficiency in the test language was below 5 (out of 7), and to the high-proficiency group otherwise, resulting in 183 participants in the high-proficiency group (HP), 312 participants in the low-proficiency group (LP), and 249 participants in the native-language group (L1). Participants' profiles for Experiments 1 and 2 of Study 4 are summarized in Table 2. For Experiment 1, participants were recruited through an online survey system (www.soscisurvey.de). For Experiment 2, participants for online data collection were recruited through university mailing lists, social media, and dedicated websites. Participants in the classroom studies of Experiment 2 were recruited in psychology and law B.A. seminars and lectures at the Freie Universitaet Berlin as well as a linguistics seminar at the Humboldt-University Berlin. All participants of Study 4 received no monetary reimbursement but participated out of interest.

Table 1: Summary of participants' profiles in studies 1 – 3.

				reading rates w/min		self-report		
			Lextale	*real words*	*pseudowords*	*Age of acquisition (years)*	*Proficiency (1 -7)*	*Accent (1-7)*
Study 1	N = 28							
	L1	mean	90.4	117.4	73.5	-	-	-
		SD	4.9	23.7	21.2	-	-	-
	L2	mean	72.7	81.3	57.0	8.5	5.0	3.13
		SD	11.2	12.5	8.5	2.38	0.97	1.39
Study 2								
Exp. 1 N = 25	L1	mean	90.8	131.4	83.5	-	-	-
		SD	6.9	10.2	17.5	-	-	-
	L2	mean	80.5	124.0	81.3	9.7	6.0	2.4
		SD	8.7	9.0	13.5	1.64	0.5	1.0
Exp. 2 N = 25	L1	mean	90.4	130.0	83.5	-	-	-
		SD	5.0	14.0	20.0	-	-	-
	L2	mean	77.0	123.2	78.6	9.3	5.9	2.7
		SD	13.0	9.5	10.6	2.0	0.4	0.8
Study 3	N = 28							
	L1	mean	91.79	131.6	84.82	-	-	-
		range	80-100	111-154	58-110	-	-	-
	L2	mean	81.31	124.1	77.76	9.8	5.9	2.6
		range	60 -100	108-140	43 - 107	3.5 - 13	5 - 7	1- 4

Table 2. Summary of participants' language profiles for Experiments 1 and 2 of Study 4.

Study	Test language	Participants‘ profile			Self-report of test language proficiency [a]				
		n	Sex in % female	Age in years (SD)	Read	Write	Speak	Listen	mean
Experiment 1									
	L1	249	56	31 (10.2)	-	-	-	-	-
	HP	183	68	30 (9.0)	6.0 (0.6)	5.3 (0.8)	5.4 (0.9)	5.7 (0.7)	5.7 (0.6)
	LP	312	68	29 (8.1)	3.7 (1.0)	2.8 (0.9)	2.8 (0.8)	3.2 (1.0)	3.1 (0.8)
Experiment 2									
online	L1	203	74	28 (7.9)	5.6 (1.0)	5.0 (1.2)	4.9 (1.2)	5.3 (1.2)	5.2 (1.0)
	FL	218	81	24 (5.7)	5.6 (1.0)	4.9 (1.1)	4.9 (1.3)	5.0 (1.2)	5.1 (1.0)
lab/ classroom	L1	193	58	25 (5.6)	-	-	-	-	-
	FL	180	62	24 (5.1)	[b]	[b]	[b]	[b]	5.1 (0.9)

[a] On a Likert scale of 1 (single words) – 7 (native level).

[b] Only overall proficiency ratings collected.

L1: native language, HP: high proficiency, LP: low proficiency, FL: foreign language. Data are given as counts, percentages, or means (SD).

3.2. Psycholinguistic variables

The aim of this section is to provide an overview of word and pseudoword properties that are known to influence sublexical and lexical processing of visually presented words and pseudowords, and that were either controlled for or manipulated in Studies 1 – 3. At the sublexical level bigram frequencies were controlled for in Study 1 and manipulated in Studies 2 and 3. At the lexical level, the frequency of occurrence of single words is known to have a major influence on speed and accuracy of single word recognition, alongside with orthographic neighborhood sizes (Balota et al., 2004; Brysbaert et al., 2011). While word frequency was only of importance in Study 1, as the other studies employed pseudowords with word frequency 0 only, orthographic neighborhood sizes were controlled for in Study 1 and manipulated in Studies 2 and 3. In the following, the computation and analysis of different bigram frequency variables and orthographic neighborhood sizes is described in detail.

All psycholinguistic variables were calculated based on word frequency counts from the SUBTLEX corpora of German and English (New, Brysbaert, Veronis, & Pallier, 2007) using custom-made software written in MATLAB (version 7.10.0, Mathworks Inc., Natick, Massachusetts) and the free statistical package R (R Core Team, 2012). The SUBTLEX corpora contain comprehensive sets of film subtitles and feature modern colloquial language, providing frequency counts that reflect daily language use. The German SUBTLEX contains frequency counts for over 100 000 separate word forms and the English SUBTLEX contains word frequency counts for over 75 000 separate word forms. Subtitle word frequencies were previously shown to be good predictors of word processing times in naming and lexical decision (Brysbaert et al., 2011).

All frequencies were normalized per million units (i.e. word frequencies were normalized per million words and bigram frequencies per million bigrams), providing a measure that is independent of corpus size.

3.2.1. Sublexical statistics

Bigram frequencies refer to the frequency of occurrence of series of two letters within single words. Based on the whole-word frequency counts in SUBTLEX, I calculated frequencies of occurrence for all possible bigrams in German and English. In the next step I then calculated mean bigram frequencies for words in each of the languages, which provided a measure of sublexical typicality of a letter string for each of the two languages. These values were then used to calculate mean bigram frequencies for words of both languages, as well as for other letter string.

One of our aims was to compare between bigrams of German and English, in particular to define bigrams that are legal in only one of the languages, but do not appear in the other language, coined *orthographic markers* (investigated in Study 2). Legality of bigrams is often constrained to certain positions within a word (i.e. the bigram ‘le’ is a legal word ending in English, but not in German, whereas the bigram ‘gh’ is frequent in English but illegal in German independently of its position in a word). For this reason we chose to calculate separate bigram frequencies for word onsets, word middle positions, and word end positions.

While initially bigram frequencies were calculated based on the complete SUBTLEX corpus, we found that bigram frequency of orthographic markers is not necessarily 0 in the respective other language in this case, because these letter combinations could occur in rare cases at the boundaries between (otherwise free) morphemes, or in loan words and proper names. For example, the German arker *pf* occurs in English words such as *cupful* or *campfire* but never as a grapheme, within a morpheme, or syllable. Similarly, the English marker *th* occurs in German names (e.g. *FuerTH*), Greek loan words (e.g. *THeologie (theology)*), and as a bigram unifying two normally free morphemes (e.g. *achTHundert, (eight hundred)*), but not as a grapheme in other etymologically German words. Since all PWs employed in our studies were mono-morphemic, we recomputed bigram frequencies based on mono-morphemic words of the relevant word lengths and defined orthographic markers as bigrams with a frequency of 0 at some word position based on this restrictive frequency count.

Based on position-specific bigram frequencies for all possible bigrams, we computed 3 different sublexical bigram frequency measures for each word in the German and English lexica. Mean German bigram frequency (mBF_G) was the average frequency of occurrence in German of all constituent bigrams of a word. Mean English bigram frequency (mBF_E) was the average frequency of occurrence in English of all constituent bigrams of a word. Moreover, for each word we identified the bigram that had the largest absolute difference value between its German and English frequencies, and took this (signed) difference value as the words’ maximal bigram frequency difference (*maxdiffBF*). Typically, for words that contained an orthographic marker, *maxdiffBF* reflected the frequency difference of the marker bigram. However, for words that contained only bigrams that were legal in both languages, it reflected the bigram frequency difference of the most discriminative bigram.

Mean bigram frequencies were employed in Study 1 to match stimulus material across languages on sublexical typicality. In Studies 2 and 3, mean and maximal bigram frequencies were manipulated as measures of sublexical language similarity to investigate its effects on language decision behavior.

3.2.2. Lexical statistics

The dynamics of lexical access are strongly determined by the similarity of a letter string to other lexical entries, called the orthographic neighborhood size. Importantly, orthographic neighborhood size is well-suited to investigate the similarity of a letter string to words of several languages, as it can be computed for letter string independently of their lexicality in the respective language.

Here we employed the Levenshtein orthographic distance to measure the orthographic neighborhood size of a letter string. The Levenshtein orthographic neighborhood size (*OLD20*) is defined as the average distance of a letter string to its 20 closest Levenshtein orthographic neighbors in a lexicon (Yarkoni et al., 2008). The Levenshtein distance between two letter strings is computed as the minimal number of letter deletions, insertions, and changes that is needed to transform their orthographic word forms into each other. *OLD20* is a variable with a strong dependency on word length, such that if a specific word length is more common in a language, the orthographic neighborhoods of words of that length are denser than for other word lengths. To control for the difference in average word length between German and English and make *OLD20* values in German and English comparable, *OLD20* was mean-normalized for each word length within each language. All language comparisons were based on normalized scores. For each word in both corpora we computed the difference (*diffOLD*) between its average Levenshtein distances to the 20 closest neighbors in the German Subtlex (OLD_G) and in the English Subtlex (OLD_E) to quantify the difference between orthographic neighborhoods in German and English. We used the "vwr" library in the statistical package R to compute *OLD20* (Keuleers, 2013).

Orthographic neighborhood size was used in Study 1 to match stimuli on lexical similarity across languages, and in Studies 2 and 3 as measure of lexical language similarity statistics.

3.3. Tasks

This section describes the tasks used in this dissertation work. Study 1 employed the lexical decision task, Studies 2 and 3 employed the language decision task, Experiment 2 of Study 3 employed the naming task, and Study 4 used the framing problems.

3.3.1. Lexical decision task

The lexical decision task is the most frequently used task in the investigation of lexical access, as it is commonly assumed that response times in this task reflect the speed with which a lexical match to the input is identified (Balota & Chumbley, 1984). As very few errors are made in this task, standard analyses involve a comparison of mean reaction times for correct responses across conditions.

Study 1 employed the lexical decision task for comparing the dynamics of sublexical identification and lexical access in German and English as a function of stimulus length. Participants performed a block of English and a block of German lexical decisions, whereby each block contained 124 words of the respective language and an equal amount of matched pseudowords. As the aim of Study 1 was to investigate length effects, there were 31 words and 31 pseudowords of lengths 3-6 in each language block. Across these conditions stimuli were matched in word frequency, orthographic neighborhood sizes and bigram frequencies (as determined based on the SUBTLEX corpora of German and English, New et al., 2007) in the respective languages to exclude confounds with stimulus length. A complete list of stimuli and their properties can be found in the Appendix for Study 1.

3.3.2. Language decision task

The language decision task is typically used to investigate the representation of language identity in bilinguals' word processing system (Casaponsa et al., 2014; Grainger & Dijkstra, 1992; Vaid & Frenck-Mestre, 2002; van Kesteren et al., 2012). As in the lexical decision task, accuracy is quite high on this task, such that standard analyses focus on differences in reaction times. Instead of words, however, pseudowords can be used, in which case in addition to reaction times participants' decisions convey meaningful information. This approach was used by Lemhöfer & Radach (2009) to show that bilinguals are able to perceive the similarity of a pseudoword to one of their languages. In such a setting, which was also used in Studies 2 and 3, participants' responses do not reflect an absolute accuracy, but rather their subjective estimation of the typicality of a letter string for the letter strings of each language. The use of pseudowords in this task has several advantages. First, pseudowords create a language-ambiguous context and thus facilitate simultaneous activation of both language systems. Second, while sublexical processing and lexical search for pseudowords and words are comparable, the use of pseudowords reduces the effects of semantics and precludes a lexical match, thus boosting the effects of sublexical information and partial lexical activation (i.e. of orthographic neighbors), which were in the focus of Studies 2 and 3. Third, pseudowords can be carefully constructed to contain task-relevant information with considerably fewer constraints than real words.

The language decision task was used with pseudoword stimuli in Studies 2 and 3 to investigate the effects of sublexical and lexical statistical information on language identity representations and language assignment. Pseudoword stimuli were carefully chosen to reduce the shared variance of mean bigram frequencies and orthographic neighborhood sizes in L1 and L2 in the stimulus set. This allowed us to pinpoint potential unique effects of each variable – an undertaking that would not be possible with real words.

Study 2 focused on the effects of sublexical and lexical statistics on language decisions in the presence and absence of orthographic markers. Thus, half of the stimuli (192 pseudowords) were orthographically marked for German or English, while the other half consisted of unmarked pseudowords that were orthographically legal in both languages. Differences between mean bigram frequencies (*diffBF*) and orthographic neighborhood sizes (*diffOLD*) were parametrically modulated in the stimulus set (reproduced in full length in the Appendix).

Study 3 focused on the neural representations of continuous L1 and L2 sublexical (mean bigram frequencies) and lexical (orthographic neighborhood size) statistics. Thus the stimulus set in Study 2 contained 432 pseudowords, which were all orthographically legal in both languages and had continuously varying values of BF_G, BF_E, OLD_G, and OLD_E.

3.3.3. Naming task

In contrast to the lexical decision and language decision tasks, naming does not require an explicit decision about an input, but rather a mapping between orthographic and phonological representations. Naming of existing words is predominantly based on assembled lexical phonological representations, whereas naming of pseudowords is assumed to recruit the sublexical reading route which transforms an orthographic code into phonological representations (Coltheart et al., 2001; Perry et al., 2010).

In Experiment 2 of Study 2 we used the naming task to investigate how sublexical and lexical similarity to German and English would affect participants' choices to pronounce pseudowords according to grapheme-to-phoneme mapping rules of one or the other language. The naming task was conducted on the same stimuli as the language decision task and response times as well as the language chosen (also referred to as naming language further below) were recorded for analyses.

3.3.4. Asian disease and other framing effect problems

A classical task producing the framing effect is the Asian disease problem, in which participants are asked to choose between a sure and a risky alternative for combating a disease outbreak (Tversky & Kahneman, 1981). Importantly, both medicines have the same expected values in terms of people saved such that there is no economic difference between the two choice alternatives (see Table 3 for the full text of the Asian disease problem).

Participants of Study 4 were presented with the Asian disease task and 2 other framing problems, which were developed specifically for this study (see Appendix). Because of the easily recognized pattern in this and other similar questions, it is not possible to present the same participant with more than a few different framing problems. Thus, to acquire a sufficient amount of data points for statistical inference data from a large sample has to be collected (at least 30 participants per experimental condition, which means above 200 participants in a 2x2x2 design as in Experiment 2 of Study 4). While the offline collection of such large data sets can be highly tedious, online data collection presents a feasible alternative, which is why a part of the data for Study 4 was collected online. Importantly a growing body of research has demonstrated that online data replicate major psychological phenomena thus suggesting that human behavior is not altered by this novel media (Crump, McDonnell, & Gureckis, 2013).

Table 3: Wording of the Asian Disease task in English.

The Expected values of the sure (Medicine A) and risky (Medicine B) options are equal. Classically, the sure option is chosen more often in the Gain than in the Loss frame.

Recently, a dangerous new disease has been going around. Without medicine, 600 000 people will die from it. In order to save these people, two types of medicine are being made. Now you have to choose, which one to use.

If you choose Medicine A,

- 200 000 people will be saved. (Gain frame)

- 400 000 people will die. (Loss frame)

If you choose Medicine B,

- there is a 33.3% chance that 600 000 people will be saved and a 66.6% chance that no one will be saved. (Gain frame)

- there is a 33.3% chance that no one will die and a 66.6% chance that 600 000 will die. (Loss frame)

Which medicine do you choose?

3.4. Data analysis

This section provides an overview of the methods used to analyze the data. I describe the methods used for inference statistics, the measurement model (diffusion model) employed in Study 1 and functional magnetic resonance imaging, which was used in Study 3.

3.4.1. Statistical analyses

Behavioral data were analyzed using analyses of variance (ANOVA) in designs with categorical independent variables (parameter estimates in Study 1), in logistic regressions for between-subject designs with binary outcome variables (participants' decisions in Study 4) and in mixed-effects regression models for designs with continuous within-subject independent variables (linear for reaction times and logistic for decisions in Studies 1 – 3).

All ANOVA analyses began with omnibus ANOVAs, which included all categorical factors of the experimental design. Significant effects were further elucidated using planned t-test comparisons and reduced ANOVAs, where appropriate. All reported effects were significant with a $p < .05$ for planned comparisons, and with a Bonferroni-correction for post-hoc analyses (J. D. Cohen, Cohen, West, & Aiken, 2013).

Designs with within-subject manipulations of continuous variables, as in Studies 1 - 3 were analyzed using mixed-effects modeling (MEM, Baayen, 2008). Mixed-effects models are better suited for such designs than ANOVAs for two reasons. First, mixed-effects models can account for within-subject effects of continuous regressors, which is not possible in classical regression analyses. Second, mixed-effects models can include several random factors. This is required in psycholinguistic designs to model random variance in participants as well as in stimuli. This approach has a higher power than classical F_1/F_2 analyses (Baayen, Davidson, & Bates, 2008). Reaction times were analyzed using linear mixed-effects models and responses were analyzed using logistic mixed-effects models. Random factor structure in all analyses, included intercepts for participants and stimuli, as well as random slopes for the highest order interaction of fixed within-subject factors. Such definition of random factor structure is preferable over a full set of random slopes in complex designs as it reduces degrees of freedom while still providing a good model fit (Barr, 2013).

All statistical analyses were conducted in the free software package R (R Core Team, 2012). Analyses of variances were conducted using the library "ezANOVA". MEMs were estimated using the R-packages lmer (Bates, Maechler, Bolker, & Walker, 2014) and coda (Plummer, Best, Cowles, & Vines, 2006).

3.4.2. Hierarchical diffusion modeling

In Study 1 the diffusion model (as described in the introduction) was fitted using the hierarchical approach (hierarchical diffusion model, HDM, Vandekerckhove et al., 2011), which allows estimating DM parameters of single participants even in sparse data sets. In HDM, the implicit assumption that all participants of an experiment stem from one population is made explicit by assuming that for each parameter, values of all participants stem from an underlying normal distribution. These constraints bound the parameter values of a single participant by the distribution defined by the parameters of all other participants, enabling simultaneous estimation of the parameters of all participants. We fitted the HDM to our data using a Bayesian approach and Markov-Chain Monte-Carlo (MCMC) approximations of the underlying distributions (for a detailed description of this approach see Vandekerckhove et al., 2011). This analysis approach resulted in parameter estimates for each participant, which were then subjected to ANOVAs.

3.4.3. Functional magnetic resonance imaging

Study 3 employed functional magnetic resonance imaging (fMRI) to investigate the neural representation of language-specific statistical information in bilinguals. fMRI allows an indirect measurement of the amount of neural activity through measurement of changes in blood oxygenation level dependent contrast (BOLD, Logothetis & Wandell, 2004). The high spatial resolution of the fMRI signal makes this method highly suitable for identifying the neural correlates of cognitive function.

In Study 3, fMRI data were acquired on a 3 T scanner (Trio; Siemens) at the Dahlem Institute for the Neuroimaging of Emotions (DINE) with a spatial resolution of 3x3x3 mm^3 voxel size for the functional images and a spatial resolution of 1x1x1 mm^3 voxel size for anatomical brain images. Data were then preprocessed using the standard pipeline in SPM 8 for

MATLAB (Mathworks, Massachusetts), including realignment, movement correction, co-registration, normalization to a template, and smoothing with an 8-mm Gaussian kernel.

We conducted univariate and multivariate fMRI analyses. In the univariate analyses the effects of independent variables were assessed separately for each voxel, with the aim to identify continuous clusters of voxels showing significant correlation between brain activation and independent variables. All reported univariate results were significant at the uncorrected peak-level of $p < .001$ and an FWE-correction ($p < .05$) at the cluster level.

We used a multivariate pattern analysis *(MVPA)* to identify brain regions in which activation patterns contained information about participants' language membership decisions even in absence of differences in the mean signal. Multivariate analysis methods are more sensitive to differences in BOLD signal change than univariate analyses, as they are based on activation patterns across voxels rather than single voxels' behavior (Norman, Polyn, Detre, & Haxby, 2006; Pereira, Mitchell, & Botvinick, 2009). MVPA was performed with linear support vector machine classifications and leave-one-out cross-validation (Cristianini & Shawe-Taylor, 2000; Pereira et al., 2009). Cross-validation examined whether classifiers trained on a subset of the data would produce above chance accuracy on an independent subset of the data. Classifiers were trained to discriminate between trials with German responses and trials with English responses based on beta value estimates for each type of trials within single runs.

Univariate analyses were conducted in MATLAB (version 7.10.0, Mathworks Inc., Natick, Massachusetts) using the statistical parametric mapping toolbox (SPM8), the marsbar toolbox (http://marsbar.sourceforge.net/), and custom-written scripts. Multivariate analyses were conducted using LIBSVM (Chang & Lin, 2011), the TDT toolbox (Hebart, Görgen, & Haynes, 2015), and custom-made scripts.

4. Dissertations studies

In this chapter I briefly summarize the four empirical studies that constitute the body of this thesis (see list of original publications).

4.1. Investigating length effects in bilinguals using a diffusion model analysis

The aim of this study was to identify the unique effects of length on sublexical encoding and lexical access in lexical decisions and to compare these effects across languages in English-German bilinguals. To this end my co-authors and I used a hierarchical diffusion model (HDM) analysis, which extracts the rate of evidence accumulation and the duration of decision-independent perceptual encoding from RT-Accuracy distributions. This model was compared to a classical multiple regression approach. Participants in this study were German native speakers with a high proficiency in English. They performed lexical decisions on 3-6 letter long words and pseudowords in a block of German and a block of English.

For both languages, the regression approach showed a decrease in RTs with length for pseudowords, but no length effect for words, in agreement with previous studies. However, HDM analysis revealed opposing effects of length on duration of perceptual encoding and rate of evidence accumulation. Specifically, perceptual encoding times increased with length for words and pseudowords, whereas the rate of evidence accumulation increased with length for real words but decreased for pseudowords. These opposing effects can explain the null effect observed for words in the classical analysis, and also account for the inconsistent findings in the field on word length effects. Moreover, these results suggest that perceptual encoding of letter strings is affected by length for words and pseudowords alike, a finding that needs to be incorporated into current models of visual word recognition.

Effects of length on perceptual encoding of pseudowords were stronger in English than in German, with no differences between languages for words. Effects of length on the rate of evidence accumulation for words were stronger for English than for German, whereas the opposite was the case for pseudowords. These findings suggest that grapheme encoding appears to be less efficient in participants' second language (English) than in their native language (German), despite their high proficiency. However, lexical search in English profited more than in German from length, possibly reflecting these lengths are more typical and thus more expected in English than in German and the increase in available perceptual evidence with length.

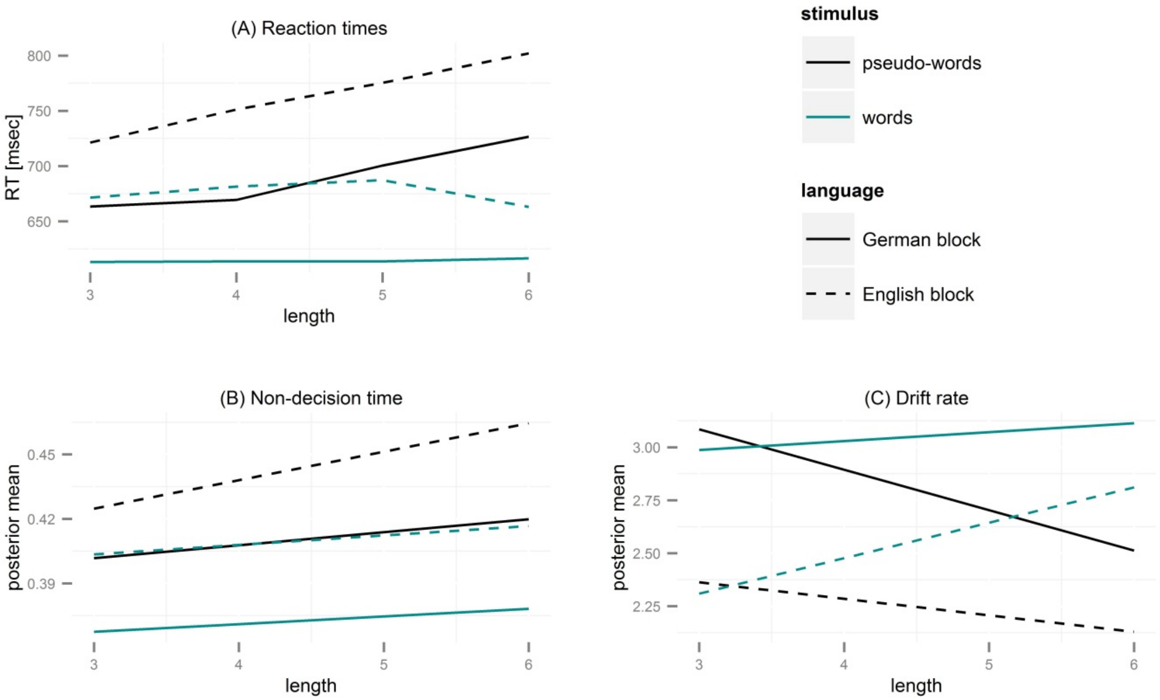

Figure 3: Length-induced changes in drift rate and non-decision time as function of stimulus type and language.

(A) Reaction times for correct responses to words and pseudowords in German and English. RTs increased for PWs but not for words with length. (B) Estimates of non-decision times for words and pseudowords in German and English based on parameters of the diffusion model. Non-decision time increased with length in all four conditions. (C) Estimates of drift rates for words and pseudowords in German and English based on parameters of the diffusion model. Evidence accumulation slowed down with length for pseudowords, but was faster for long than for short words.

4.2. Interplay of bigram frequency and orthographic neighborhood statistics in language membership decision

In this study, my co-authors and I investigated whether sublexical and lexical statistics cue language membership decisions during visual processing of single words.

In a first step, we conducted a corpus analysis of German (105 000 words) and English (76 000 words) subtitle corpora (Brysbaert et al., 2007) to identify sublexical and lexical variables that differ with respect to their statistical distributions in German and English. At the sublexical level we examined the effects of the difference in mean frequency of occurrence of the bigrams in a word between languages (*diffBF*), as well as the bigram with the maximal difference between its frequencies in German and English (*maxdiffBF*). At the lexical level we examined the effects of the size of a word's orthographic neighborhood in each of the languages (*diffOLD*, Yarkoni et al., 2008). The results of the corpus analysis showed that the distributions of *maxdiffBF* and *diffOLD* differed between German and English, whereas the distributions of *diffBF* were similar. In other words, most English words have more orthographic neighbors in English than in German. Moreover, most English words contain a bigram that is much more frequent in English than in German. The opposite was true for most German words. On the contrary, a higher mean bigram frequency in German than in English happened as often in German as in English words (middle panel of Figure 4).

Based on the results of the corpus analysis, we hypothesized that German-English bilinguals employ the difference in orthographic neighborhood sizes and maximal bigram frequency difference, but not mean bigram frequencies for language decisions on ambiguous letter strings. In Experiment 1 of this study highly proficient German-English bilinguals engaged in a language decision task on a set of pseudowords, in which all three variables were varied parametrically. Moreover, half of the pseudowords contained orthographic markers, enabling us to also investigate whether differences in continuous statistics would have an effect on the presence of orthographic markers. In Experiment 2 of this study, another group of highly proficient bilinguals (n = 25) engaged in a naming task on the same set of pseudowords. While Experiment 1 tested the effects of all three variables on explicit language decisions, Experiment 2 tested their effects in a situation where language assignment was implicitly required.

The results were that *diffBF* affected reaction times in both experiments for unmarked pseudowords only, with greater effects in naming. *MaxdiffBF* biased language decisions in the naming task but not in language decision (Figure 5). We interpret these stronger effects of sublexical statistics during naming as reflecting increased reliance on grapheme-to-phoneme encoding in this task. Finally, language attribution in both experiments was influenced by *diffOLD*, and this effect occurred even in presence of orthographic markers.

In summary, these findings indicate that bilinguals rely on continuous language-specific statistics at sublexical and lexical levels to infer language membership. Our results stand in contrast to current models of bilingual visual word recognition (i.e. the BIA+ model, van Kesteren et al, 2012), which do not link continuous sublexical or lexical statistics to language nodes.

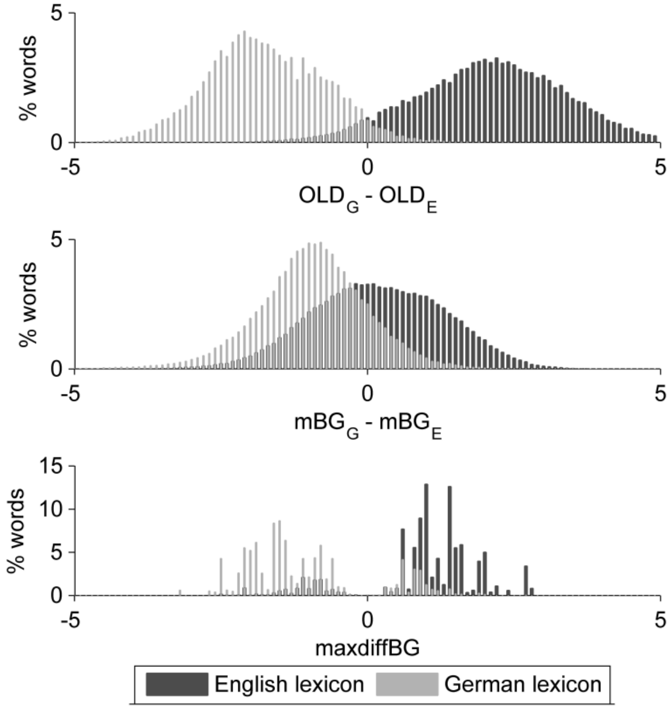

Figure 4: Distributions of language similarity statistics in German and English SUBTLEX corpora.

Upper panel: Difference in orthographic neighborhood size (*diffOLD*).Middle panel: difference in mean bigram frequency (*diffBF*). Bottom panel: maximal bigram frequency difference (*maxdiffBF*).

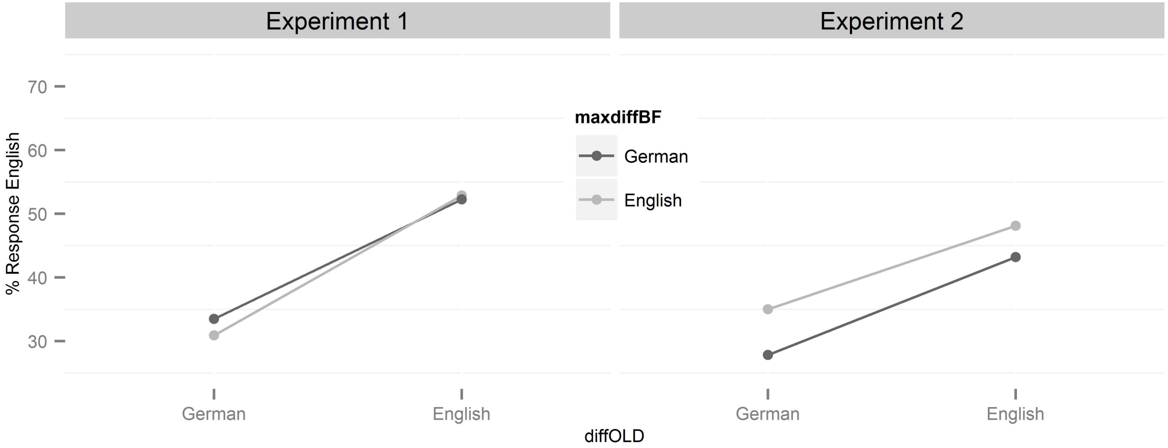

Figure 5: Effects of difference in orthographic neighborhood sizes (*diffOLD*) and maximal bigram frequency difference (*maxdiffBF*) in experiments 1 and 2 of Study 2.

4.3. The neural basis of bilinguals' language decisions

The results of Study 1 demonstrated bilinguals' ability to utilize fine-grained differences in statistical information between languages towards language decisions. Here my co-authors and I used fMRI to investigate how neural representations in the visual word processing network are affected by continuous similarity statistics to L1 and L2. Moreover, we hypothesized that language identity is encoded in distributed activation patterns within these networks. To this end, German-English bilinguals made language decisions on visually presented pseudowords during fMRI. Similarly to Study 1, the pseudowords were chosen to parametrically vary in their German and English mean bigram frequencies and orthographic neighborhood sizes.

Our behavioral results replicated our findings from Study 1 in showing that orthographic neighborhood size affected participants' decisions, whereas higher mean bigram frequencies in German (L1) lead to faster processing. Importantly, while Study 1 focused on differences in German and English statistics, here we investigated the separate contribution of similarity to German and English, finding that bilinguals were indeed taking both languages into account.

Neuroimaging results (Figure 6) revealed sensitivity to L1 statistics at sublexical orthographic (occipital lobe) and phonological (temporo-parietal lobe) levels, whereas lexical similarity to both languages correlated with neural activation in the angular gyri. Univariate analyses showed no differences between trials with response English and trials with response German. Multivariate pattern analysis, however, revealed that distributed activation patterns varied as a function of participants' responses throughout the network identified in the univariate analyses and as early as in the visual cortex.

In summary, these results demonstrate that in language-ambiguous contexts visual word processing is dominated by L1 statistical structure at sublexical orthographic and phonological levels, whereas lexical search is determined by the structure of both languages. Moreover, our results of language identity-dependent distributed activation patterns throughout the reading network provide a possible mechanism for language identity representations within this shared network.

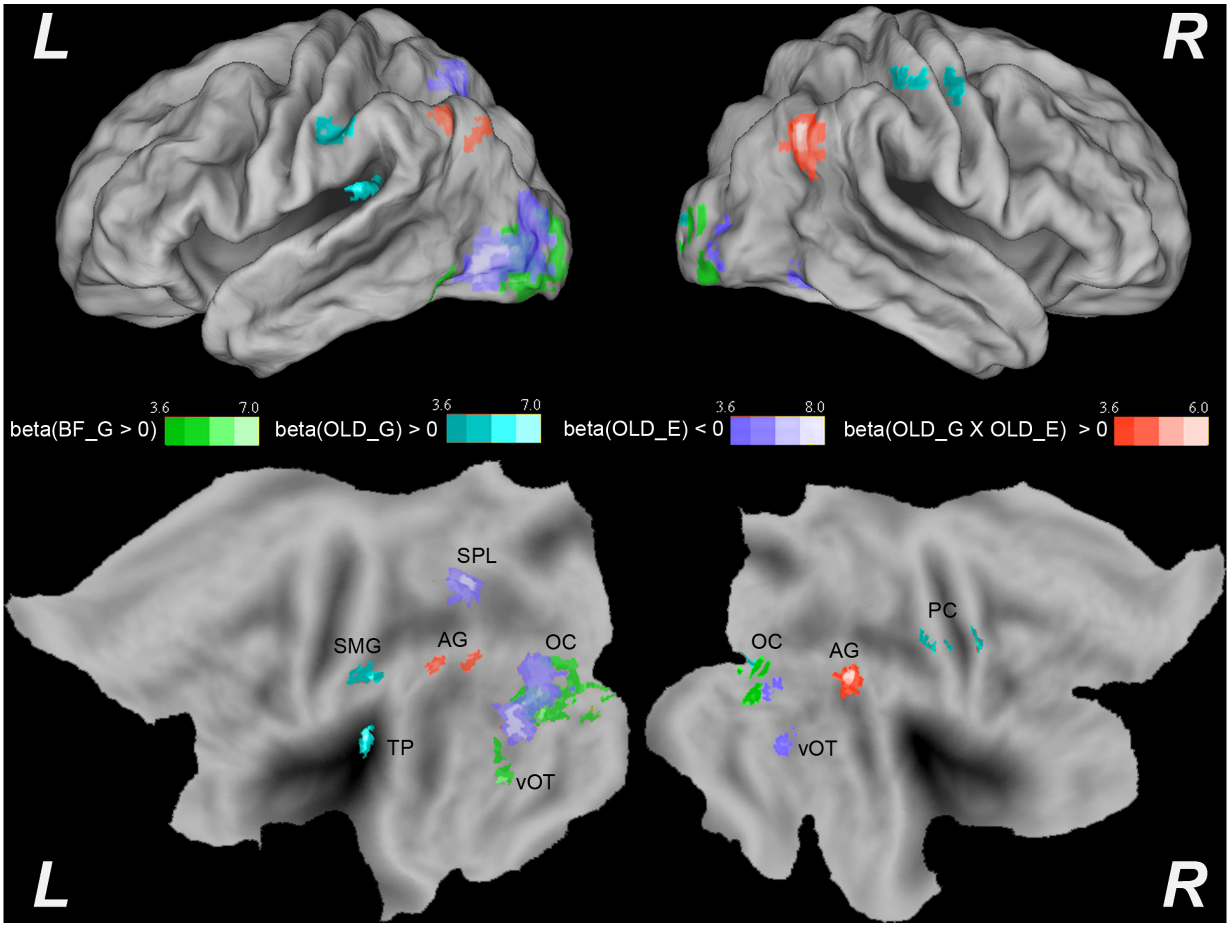

Figure 6: Maps of brain regions where the change in brain activation was modulated by one of the psycholinguistic variables independently of the response language in Study 3.

No significant activations or deactivations were found for English bigram frequency (BF_E). All clusters were significant at a cluster-level FWE-corrected $p < .05$, with peak-level uncorrected $p < .001$, heat maps reflect t-values. *BF_G* – German bigram frequency; *OLD_G* – German orthographic neighborhood; *OLD_E* – English orthographic neighborhood; OC – occipital lobe; vOT – ventral occipito-temporal cortex; TP- parieto-temporal junction; SMG – supramarginal gyrus; PC – postcentral gyrus; SPL –superior parietal lobule; AG – angular gyrus.

4.4. Affective processing and cognitive control during decision making under risk in a foreign language

The aim of this study was to investigate predictions of two accounts of reduced framing effects during foreign language use: The emotional distance account and the cognitive control account. Experiment 1 investigated a direct prediction of the emotional distance account, namely that foreign language effects on decision making would disappear with increasing proficiency. Experiment 2 simultaneously investigated both accounts by contrasting decision making in a consistent language context with decision making immediately following a language switch.

In both Experiments native speakers of German were presented with the Asian disease problem either in German or in a foreign language. In Experiment 1 we tested a central prediction of the emotional distance account, namely that the framing effect would be reduced at low, but not high, foreign language proficiency levels. We found a strong framing effect in the native language, and surprisingly also at all proficiency levels in the foreign language, contrary to the predictions of the emotional distance account. In Experiment 2 we orthogonally manipulated foreign language use and language switching to concurrently test the validity of both accounts. As in Experiment 1, foreign language use per se had no effect on framing. Crucially, the framing effect was reduced following a language switch, both when switching into the foreign and into the native language, with somewhat stronger effects when switching into the foreign language (Figure 7). This result suggests that reduced framing effects are not explained by increased emotional distance in a foreign language, but by transient enhancement of cognitive control, putting the interplay of bilingualism and decision making in a new light.

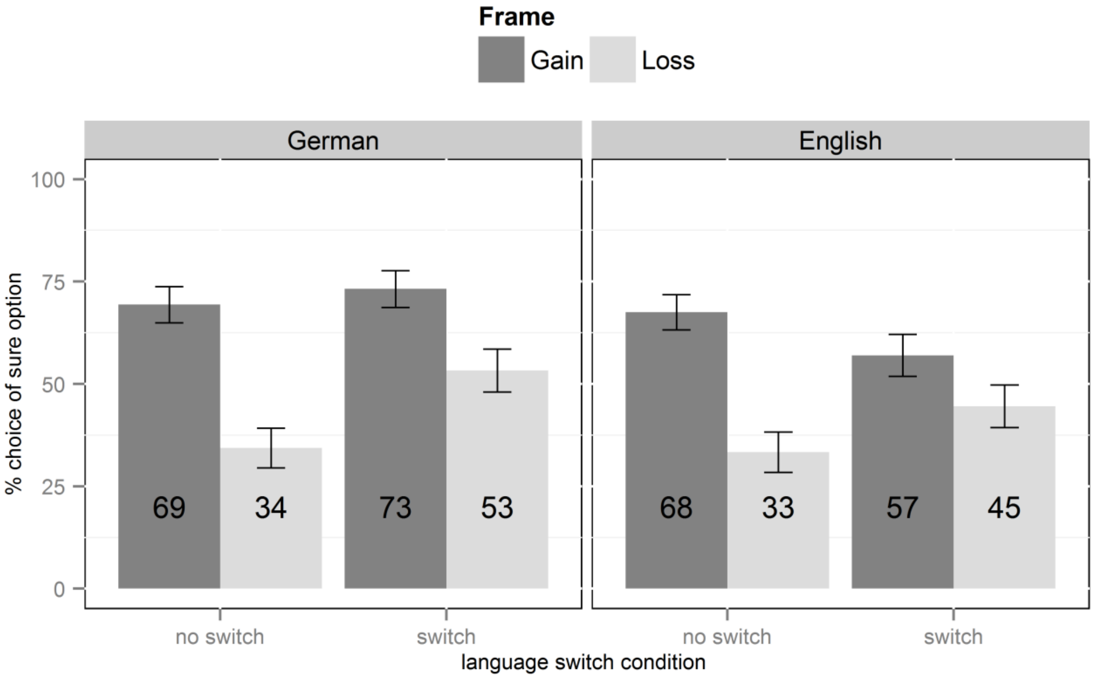

Figure 7: Results of the Asian disease task in Experiment 2 of Study 3.

The framing effect was equally strong for in the German and English conditions, when the instructions were in the same language as the task. However, when participants switched languages between instructions and task, the framing effect disappeared in English and was strongly reduced in German.

5. Discussion

In this chapter I begin with a short discussion of the empirical results with respect to my initial research questions. After that I embed my results in a more general theoretical framework. I refer to the appendices for detailed discussions of each of the four studies.

5.1. Discussion of research questions

1. Is seriality in sublexical processing, as indicated by length effects, confined to the sublexical route or is sublexical processing as required for lexical access also serial? (Study 1)

The decomposition of lexical decision RTs into non-decision times, reflecting sublexical encoding, and evidence accumulation, reflecting the dynamics of lexical activation, allowed us to directly address this question. Sublexical encoding of words and pseudowords alike was slowed by length, indicated by an increase in non-decision times, which is commonly seen as a marker of serial processing (Ziegler et al., 2001). Notably, length effects were smaller in words than in pseudowords, which we interpret in terms of facilitative top-down influence from the lexicon for real words. Furthermore, our data suggest that the lack of length effects on word RTs in regression analyses in our and previous studies is due to faster lexical access for longer words, evident in increased rate of evidence accumulation for longer words. This is a novel finding, the incorporation of which requires a revision of current models of visual word recognition. In summary, our results provide evidence for serial encoding of letter strings prior to lexical access and independent of stimulus lexicality.

2. What are the effects of the orthographic consistency of bilinguals' L1 and L2 on grapheme-to-phoneme mapping in each of the languages and how do they compare to monolinguals of the respective languages? (Study 1)

This question was approached in a comparison of sublexical encoding in German-English bilinguals, who performed the lexical decision task in each of their languages. Our results showed a larger effect of length on non-decision times in English (an inconsistent orthography) as compared to German (a consistent orthography), suggesting that German native speakers did not switch to processing of letter strings in larger chunks when reading in

English, as was found in native speakers of English (Ziegler et al., 2001). Additionally, the diffusion model analysis allowed for a comparison of rates of evidence accumulation. We found that the dynamics of lexical access were adjusted for the second language structure, evident in stronger facilitative effects of length on lexical access in English than in German. Thus, our results suggest that second language structure is incorporated in lexical processing, whereas sublexical encoding follows the structure of the L1.

3. How is language membership information represented in the bilingual visual word recognition system, and are bilinguals' decisions on the language identity of letter strings affected by continuous sublexical and lexical language similarities? (Studies 2 and 3)

An analysis of the effects of continuous sublexical (bigram frequencies) and lexical (orthographic neighborhood sizes) L1 and L2 statistics on language decisions of German-English bilinguals revealed effects of continuous statistics on language decisions. Effects of lexical language similarity statistics were preserved even for letter strings containing orthographic markers, and in a naming task, which did not require lexical activation. Overall, these data provide compelling evidence for bilinguals' sensitivity to continuous statistics, and suggest that input to language membership representations in the bilingual visual word processing system is continuous and not categorical.

4. How are sublexical and lexical language similarity statistics represented in the neural network underlying visual word processing? (Study 3)

In Study 3, brain activity of German-English bilinguals was recorded using fMRI, while they performed language decisions on pseudowords of varying sublexical and lexical similarity to German and English. The findings were that the language processing network is sensitive to first and second language similarity statistics, albeit to a varying degree. Specifically, activation of left-hemispheric regions (ventral temporo-occipital cortex, supramarginal gyrus, and temporo-parietal junction), previously associated with sublexical orthographic and phonological processing, increased with similarity to the native language, but was unaffected by similarity to the second language. On the contrary, activation of the angular gyrus, a region associated with lexical access, was modulated by lexical similarity to both languages, reflecting the ambiguity of language decisions. These results provide evidence the involvement of the angular gyri in language independent lexical access to an integrated lexicon, whereas sublexical orthographic and phonological processing appears dominated by frequency statistics of the L1.

5. Does the neural network underlying visual word processing contain language identity information, and if so what parts of it? (Study 3)

Univariate analyses of the data in Study 3 showed no difference in brain activation between trials on which participants categorized pseudowords as English and trials with categorization German. However, we a-priori hypothesized that language identity might be represented in distributed activation patterns. Thus we used a multivariate approach to compare distributed activation patterns between trials with responses English and German. The results of this multivariate analysis were in accordance with our hypothesis. Namely, activation patterns in the brain regions, which were modulated by language similarity statistics, reflected participants' language decisions. Furthermore, we found that activation patterns in two additional clusters in right association cortex in the parietal lobe also encoded language decisions. Overall, the multivariate analyses suggest that language identity information is encoded in population activity both within and outside the core visual word processing network.

6. How does the language in which information is presented affect non-linguistic decision making, such as decisions under risk, and how are these effects altered by language switching (Study 4)?

My co-authors and I addressed this question in Study 4, where we chose to focus on the framing effect as a classical example of a decision making bias. Two experiments investigated to which degree alterations of the framing effect during foreign language use depend on the foreign language proficiency and on the consistency of the language context. Our results contradict recent reports of reduced framing effects during foreign language use (Costa, Foucart, Arnon, et al., 2014; Keysar et al., 2012), in showing framing effects of comparable magnitude in foreign and native languages independently of foreign language proficiency. Yet, the framing effect was reduced following a language switch, regardless of whether to the foreign or the native language. Overall, our results show no direct effect of foreign language use on risky decisions, speaking against an explanation based on emotional distance. Rather, they suggest that the framing effect was attenuated through an increase in cognitive control demands, presumably required for language switching. Increased cognitive control might affect decision making either directly or through a temporary suppression of affective processing.

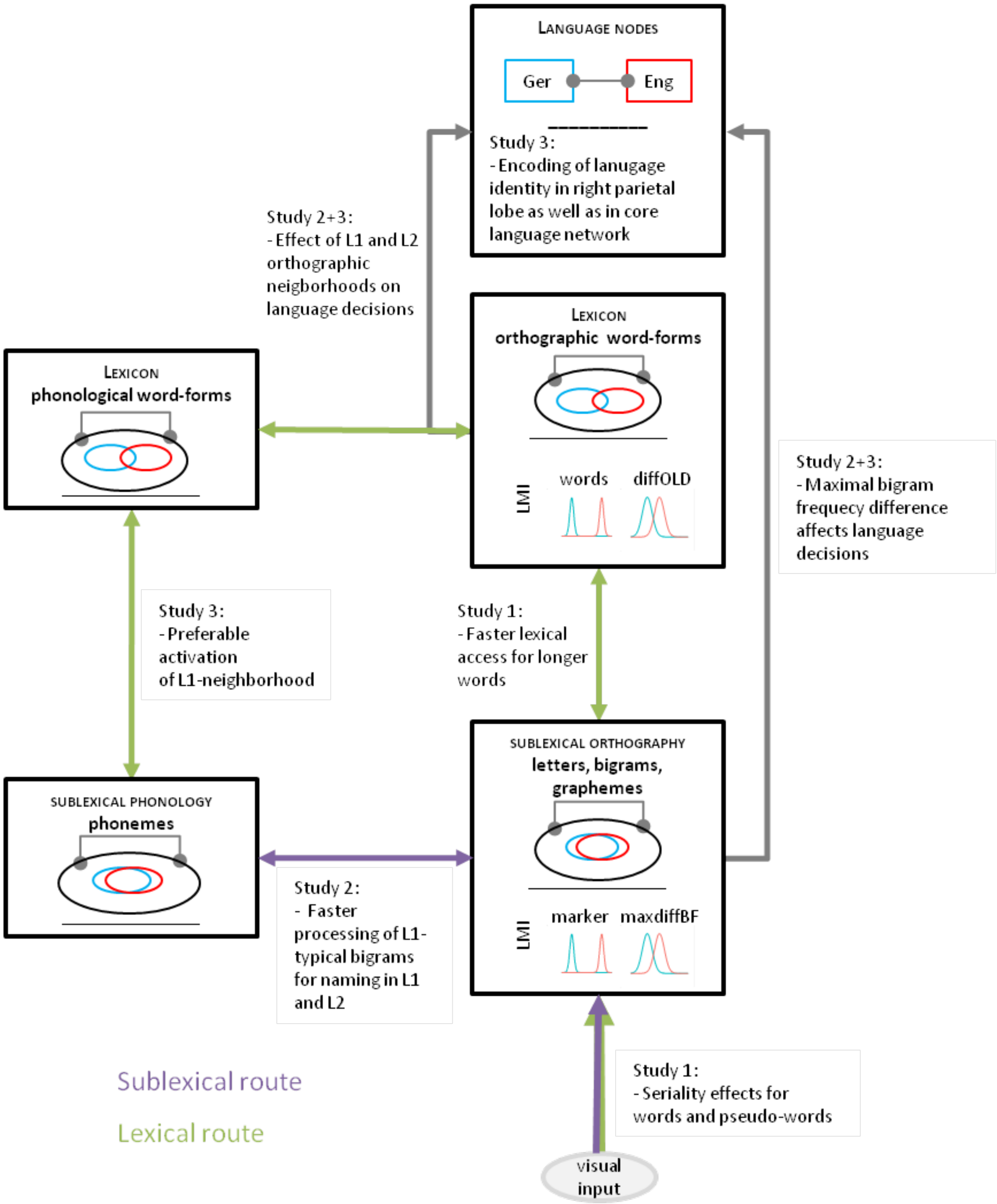

Figure 8: of the results of studies 1 – 3, integrated in a dual-route mode model of bilingual visual word perception.

5.2. A neuro-cognitive model of bilingual visual word processing

This section outlines the integration of Studies 1 – 3 into a neuro-cognitive model of bilingual visual word recognition, using CDP+ and BIA+ models as reference points (see Figure 8 above).

5.2.1. Visual processing and sublexical encoding

A major conjecture concerning sublexical encoding of letter strings is that recognition of pseudowords, but not words, involves serial processing, as indicated by inhibitory length effects for pseudowords but not for words in naming (Barton, Hanif, Eklinder Björnström, & Hills, 2014; Rastle & Coltheart, 1998). CDP is the first model into which this difference has been incorporated, solving the problem of absent length effects in lexical decision (Perry et al., 2007, 2010). The diffusion model analysis in Study 1 sheds new light on length effects in lexical decision on words, suggesting that their previously reported absence is due to a cancelling out of two opposing effects: slowing of sublexical processing and acceleration of lexical access with length. This result suggests that actually, serial encoding is not confined to the sublexical reading route but rather a necessary component of sublexical processing. While our data provide no conclusive evidence for the exact localization of length effects within the sublexical processing pipeline, the difference between length effects in English and German in our and previous reports (Goswami et al., 2003; Ziegler et al., 2001) suggests that seriality effects originate in linguistic and not visual processes, as previously suggested by O'Reagen and Jacobs (1992) and others (Nazir et al., 1991). Assuming that sublexical processes are shared between words and pseudowords, the question remains why length effects are different between the two types of stimuli. I would like to note that greater length effects for pseudowords than for words can be explained through top-down feedback from lexical representations, which can speed sublexical recognition of words, conceptually similar to the word superiority effect (Rastle, 2007).

Moving to the comparison between participants' first and second languages, the difference between sublexical length effects in German and English was the opposite of the pattern expected based on monolingual literature and the Grain size theory (Ziegler & Goswami, 2006). Specifically, the increase in non-decision times was greater in English than in

German, in particular for pseudowords. I suggest that this finding results from L1-dominance in sublexical processing, which, however, might be specific to the case of two languages with shared orthography.

The finding of sublexical L1 dominance is also supported by Studies 2 and 3, which show that in a language-ambiguous setting, letter strings are processed faster if their constituent bigrams are more frequent in the L1 than in the L2. Converging evidence also comes from the neuroimaging data in Study 3. We found that mean bigram frequencies of letter strings in participants' first but not second language were correlated with changes in BOLD signal in VWFA in ventral temporo-occipital cortex, a region dedicated to the processing of letter strings (Dehaene & Cohen, 2011; McCandliss, Cohen, & Dehaene, 2003). As participants' RTs reflected L2 bigram frequencies, the lack of corresponding neuronal activation is likely due to additional variance in L2 representations across participants or a more distributed representation within participants (Dehaene et al., 1997). I would like to note that the importance of bigram frequencies for sublexical analysis might differ between languages of varying orthographic consistency. Namely, in consistent orthographies, such as German, bigrams correspond more closely to functionally relevant orthographic units than in deep orthographies, such as English. This could be the reason for the fact that no correlation was observed between occipital activations and for English bigram frequencies. Future cross-linguistic studies are required to test this hypothesis.

Overall the results of all three studies speak in favor of bilinguals' sensitivity to the sublexical structure of first and second language, but with a processing advantage for L1-similar letter strings.

5.2.2. Lexical organization and lexical access

The BIA + model of bilingual visual word recognition (Dijkstra & van Heuven, 2002) contains an integrated lexicon, with language-nonselective activation of lexical nodes. The diffusion analysis of lexical decision RTs in Study 1 provides insight into the dynamics of lexical activation in German-English bilinguals' first and second language, showing a differential effect of length between languages. Namely, the acceleration of lexical access with length was greater for English than for German words, suggesting an adjustment to language-specific structures, as slowed lexical access would otherwise be expected for the L2. It should be noted, though, that no isolated description of lexical access dynamics exists separately for monolinguals’ of each language, it is not possible to draw inference as to whether these dynamics reflect differences between L1 and L2 or between English and German.

New and colleagues (2006) were the first to provide evidence, albeit from classical analysis of reaction time data, for faster lexical decision with increasing word length and suggested that this effect might be due to the high frequency of medium-long (4-7) words in the English language. Our data are in line with this account, as German words are on average longer than English words, which can explain why the effect of length of evidence accumulation was less pronounced in our German data. Future studies are required to further test these suggestions and to compare them across languages.

Data from studies 2 and 3 provide evidence for language-nonselective lexical access, and associate lexical access to both languages with the bilateral angular gyri. This finding extends previous neuroimaging studies in monolinguals (Binder et al., 2003) to the bilingual case, and provides the first direct neuronal evidence for concurrent activation of orthographic neighborhoods of both languages, as postulated by theories of nonselective lexical access.

5.2.3. Phonological encoding

The naming experiment of Study 2 investigated whether phonological representations of both languages are activated during naming in a language-ambiguous context. Previous studies suggested that phonological encoding is language-nonselective, mostly based on findings from word or picture naming tasks, which activate phonology via lexical representations (Colomé, 2001; Costa, Roelstraete, & Hartsuiker, 2006; J. F. Kroll, Bobb, & Wodniecka, 2006). Experiment 2 of Study 2 provides converging evidence from a language-ambiguous pseudoword naming task. It showed that lexical activation of orthographic neighborhoods in both languages affects the selection of phonological representations. The use of pseudowords allows us to infer that activation of phonological representations on the sublexical route is language-nonselective as well. Moreover, the orthographic neighborhood effects in this Experiment suggest that the choice of a language for naming in a language-ambiguous context is made on the phonological level, where lexical and sublexical orthographic inputs converge, and not at the grapheme-to-phoneme mapping stage.

Although the language decision task in Study 3 did not require phonological activation, there was increased activation in supramarginal gyrus and temporo-parietal junction for stimuli with large German orthographic neighborhoods. These regions were previously implicated in phonological encoding (Hickok & Poeppel, 2007). Based on these previous findings, I suggest that this activation in our study reflects automatic activation of phonological representations of the native, but not the foreign language (Spalek, Hoshino, Wu, Damian, & Thierry, 2014).

5.2.4. Neuro-cognitive representation of language membership information

Studies 2 and 3 were dedicated to bilinguals' ability to identify the language of a word independently of contextual cues. Previous studies focused on dichotomic language membership cues, such as the language of a language-unique word-form, or orthographic cues (Casaponsa et al., 2014; Casaponsa & Duñabeitia, n.d.; Vaid & Frenck-Mestre, 2002; van Kesteren et al., 2012). My co-authors and I extended these findings to continuous statistical patterns that differ between languages and thus can act as cues to language identification.

At the sublexical level, Study 2 showed that maximal bigram frequency difference, i.e. the frequency difference of the bigram with the largest frequency difference between German and English, affects language identification, in particular when the aim of the task was phonological encoding. This result suggests that language membership representations (language nodes) receive input not only from dichotomic sublexical cues, but also from other sublexical representations, proportional to their relative language typicality. Moreover, my co-authors and I noted that the maximal bigram frequency difference of marked stimuli equaled to the frequency difference of the marker bigram, and was greater than for unmarked stimuli. Based on this finding, I argue that the taxonomy of dichotomic and continuous language membership information needs to be reexamined and possibly abandoned in favor of one continuous source, namely bigram frequency difference, with marker bigrams at its extreme ends.

At the lexical level, we found that differences in orthographic neighborhood sizes had a strong effect on language decisions. Study 3 further refined this result, showing that this effect was due to sensitivity to neighborhood sizes in both languages. This shows that continuous statistics at the lexical level also affect the activation of language membership representations, contrary to what is currently implemented in the bilingual interactive activation model

(Dijkstra & van Heuven, 2002). Importantly, differences in orthographic neighborhood size influenced language attribution independently of marker presence, suggesting that activation is propagated from the lexicon to language nodes even if a decision can be made based on sublexical evidence. However, his was the case for L1-marked, but not for L2-marked pseudo-words. We interpret this difference as evidence for a more explicit representation of illegality for the L1, than for the L2, which is well in line with my hypothesis of L1-dominance in sublexical representations.

Analyses of neuronal activation patterns in Study 3 provide first fMRI evidence for the neural correlates of language identity representations. First, distributed activation patterns throughout the left-hemispheric word processing network differed between trials on which participants attributed inputs to English and German[2]. This result suggests that language membership information is encoded within each of the representational levels in the visual word processing network, contrary to the current architecture of BIA+. Second, activation patterns also differed between German and English categorized trials in a cluster in the right parietal lobe. Areas in proximity of this cluster were identified as crucial for a correct choice of a language for an utterance, based on lesion studies (Pötzl, 1930). Thus, this finding may be a neural correlate of abstract language identity representations, as postulated by the BIA+ model.

Our results require a reevaluation of the language membership representations currently implemented in the BIA+ model regarding the following two aspects. First, the effects of continuous language similarity statistics on language decisions necessitate the addition of connections between language nodes and non-unique representations at the sublexical level. Furthermore, the model has to be extended to allow for propagation of activation from the lexicon to language nodes, not only after identification of the target word but immediately, and from all activated items in the lexicon. These newly added connections have to reflect the amount of language identity information contained in a sublexical or a lexical node. A feasible implementation of this requirement would be to set connection strength to each of the language nodes to the value of the language similarity statistic.

The second issue is more complex and pertains to our finding of distributed language membership information throughout the neuronal network for visual word processing. I

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[2] Note that these differences emerged in absence of differences in mean activations between trials with English and German responses.

propose that this finding reflects the internal clustering of representations within each representational level according to their similarity. Such clustering would naturally result in language-specific clusters, as nodes are more similar within than between languages as shown in our and previous corpus analyses (Shook & Marian, 2013).

Previous studies of bilinguals' visual word processing found no difference between brain activations in response to words of the two languages (Costa & Sebastián-Gallés, 2014; Klein et al., 2006). While these results were well in line with theories of an integrated lexicon, they left open the question of bilinguals' ability to identify the language of an input. Our approach showed that the reason for the lack of differences between neural responses to L1 and L2 in previous studies is the nature of these differences. Namely, we also found no difference in mean activations between L1 and L2 trials on the single voxel level, but distinct distributed activation patterns for each of the two languages. This result stresses the importance of different spatial scales in the neuronal representation of information, similar to what was previously found in other areas, such as visual processing, decision making and others (Norman et al., 2006).

To conclude this section, the results of the current work extend our understanding of bilinguals' language identification. They demonstrate that bilinguals are sensitive to language similarity statistics at different levels, and that they employ this information to classify input into languages. Furthermore they imply that language membership is present in the word recognition system even when it is not unequivocally determined by the presence of a definitive language cue or lexical access to one language but not the other.

5.3. Effects of bilingualism on non-linguistic decision making

In Study 4 my co-authors and I investigated effects of foreign language use that extend beyond the immediate processes of visual word recognition, to semantic integration of the input with cognitive and affective processing in a decision making task. Our results contradict previous findings of altered decision making under risk in bilinguals(Costa, Foucart, Arnon, et al., 2014; Keysar et al., 2012), and instead suggest that decision making under risk is altered in language switching settings rather than generally during foreign language use. These findings are best interpreted as resulting from increased levels of cognitive control during language switching, rather than an increase in emotional distance during foreign language use. However, the exact mechanisms by which cognitive control and affective processing interact in decision making under risk are still not well understood (De Martino et al., 2006; Phelps, Lempert, & Sokol-Hessner, 2014; Whitney et al., 2008). Thus we cannot distinguish whether increases in cognitive control levels modulated decision making processes directly, or through a transient suppression of affective processing, which was previously suggested to be generally reduced during foreign language use (Pavlenko, 2012).

Understanding the source of the difference between our and previous findings is essential for an integration of models of linguistic and non-linguistic cognition. Two major alternative explanations exist for this discrepancy: (1) differences between samples and (2) undocumented differences in language context in previous studies. I deem cultural and linguistic differences between samples an unlikely explanation, as previous reports of FL effects on decision-making tested a variety of Western societies without finding any systematic differences between them (including English/French in Keysar et al., 2012, and Spanish/English in Costa et al., 2014). Moreover, a large body of literature that investigated cultural differences in framing effects and decision making under risk found no such patterns that could explain the magnitude of foreign language effects previously reported (Henrich, Heine, & Norenzayan, 2010; Korn et al., 2014; Kühberger, 1998). Furthermore, framing effects in the native language were comparable in our and previous reports. Language context, however, is a likely reason for divergence between our results as (possibly unintended) language switches can easily occur when a large group is simultaneously tested in a foreign language setting — especially in a classroom setting.

Our data directly link between the impact of bilingualism on cognitive control and decision-making. They are in line with recent reports of a short-term increase in executive function when bilinguals are placed in a context of frequent language switching (Wu & Thierry, 2013). Moreover, we extend it from a timed perceptual task to a complex and untimed decision-making task. It is however important to note that our findings only pertain to foreign language effects on decision making under risk, but not other types of social decision making, such as moral behaviors (Costa, Foucart, Hayakawa, et al., 2014; Geipel et al., 2015), in which different processes might be involved. Thus our data do not speak against emotional effects in decision making, but rather in favor of a differentiated investigation of affective involvement in different decision making tasks.

5.4. Limitations

Several factors should be acknowledged when discussing the general scope of the theoretical implications of the data presented in this thesis.

A general issue in bilingualism research is whether findings from a certain bilingual population can be generalized to other L1/L2 combinations. The response to this question depends on the specificity of findings to linguistic properties of the two languages and the order in which they were acquired. As such, In Study 1 we investigated aspects of the bilingual visual word recognition process that depend on the orthographic depth of the two languages. Consequently neither our results – nor the theoretical reasoning - can be extended to an arbitrary language combination. They might, however, generalize to other native speakers of shallow orthographies with a deep L2. On the contrary, very different results might be expected for the opposite combination (i.e. English native speakers of German), as a deep native language might shape the visual word processing system differently. Similarly, Studies 2 and 3 compare specific sublexical and lexical statistics of two languages. While the general approach can be easily transferred to other language combinations, other variables might contain more language membership information for other language combinations, For example, the amount of language membership information contained in bigrams or orthographic neighborhoods might be far smaller for other language combinations, which would require the definition of alternative Language similarity statistics.

Furthermore, Studies 1 – 3 of this dissertation were conducted on a specific bilingual population, namely native speakers of German who acquired English as a second language in adolescence. As our participants were clearly German-dominant, future research is required to extended our findings to more balanced bilingual populations. For example, the finding that sublexical orthographical processing follows L1 patterns might be altered for more balanced bilinguals or individuals who are immersed in their L2. Along the same lines, the pattern of results in Studies 2 and 3 might not hold for bilinguals of lower proficiency in their L2 or more balanced knowledge of both languages.

A last consideration that pertains to all four projects presented here is the differentiation between bilingualism and multilingualism. Although we referred to our participants as bilinguals, many of them are in fact multilingual as they are fluent in at least one additional language. This is the case in most bilingualism research conducted in European countries with intensive foreign language education in high school, e.g. Germany, the Netherlands, or Sweden. As recent studies suggest that knowledge of a third language leads to interaction effects with the first two languages (Dijkstra & van Hell, 2003; Lemhöfer, Dijkstra, & Michel, 2004), it is important to keep track of participants' knowledge of other languages even if controlling for it might be an unfeasible constraint. While the number of participants in Studies 1 – 3 was too small for a statistical analysis of the effects of multilingualism, we tested whether foreign language effects in Study 4 depended on participants' level of multilingualism. We found that in fact most of our participants spoke between 3 and 5 languages, but that the pattern of effects was not influenced by the exact number of languages spoken by participants. Thus we cannot exclude that the pattern of results would differ in true bilinguals, multilinguals appear to exhibit a framing effect in native and foreign languages.

5.5. Open questions and future research directions

In this closing section I discuss research questions that arise from the findings presented in this thesis.

5.5.1. Single word processing and language membership representation

This dissertation work focused on visual processing of single words. However, words are more frequently part of a sentential context, creating predictions that affect the processing of single words within and across languages (Elston-Güttler, Gunter, & Kotz, 2005; Libben & Titone, 2009; Titone et al., 2011). However, no research to date has investigated the interaction of contextual language membership information and such contained within a letter string, as in Studies 1 – 3. For example, what kind of contextual information would override the language of an orthographic marker in naming? This could depend not only on the strength of the contextual information, but also on second language proficiency and experience with language mixing. Specifically, the extent to which language context creates predictions is likely to be dependent on whether or not a bilingual individual is used to mixed-language inputs. In the same vein, predictive information from preceding inputs is likely to mitigate the effects of word length. A strong expectation for a certain word could pre-activate the corresponding sublexical representations, thus reducing the need for serial encoding (similar to the mechanism suggested for the difference between length effects in words and pseudo-words discussed above).

Furthermore, the use of pseudowords in Studies 2 and 3 isolated variables of interest and reduced the influence of semantic factors and successful lexical matching. However, it only partially reflects real-life situations, where inputs usually consist of existing words. It is an important question whether the effects of continuous language membership cues persist in real words. Thus it is important to test for effects of continuous language membership information in real words.

Finally, fast and accurate recognition of the language of a word can speed processing (Casaponsa & Duñabeitia, n.d.; Yiu et al., 2015). Indeed, the present work shows that ample cues contained within a single word serve this aim. However, unexpected switches between languages are even more likely when listening to speech than when reading a text. It is thus important to investigate the nature of continuous and dichotomic language membership cues in the auditory domain, where an additional level, namely subsegmental phonetic cues (Lagrou, Hartsuiker, & Duyck, 2011; Schulpen et al., 2003), may also contribute to identification of language membership.

5.5.2. Foreign language effects on decision making

The research field of foreign language effects in decision making is rather young, with many open questions. While many recent studies provided evidence for foreign language effect in various decision making tasks, putatively entailing different decision making strategies, a theoretical framework in which these results can be compared is still lacking. One of the major obstacles to the development of such a framework is the nature of many decision making tasks. Most problems that elicit decision making biases consist of “one-shot” – problems with rich semantics (e.g. all problems used in Costa, Foucart, Arnon, et al., 2014). While this is an ecologically valid approach, its major drawback is that it provides only one data point per participant. This necessitates between-subject designs and a relatively large number of study participants, which hinders the development of fine-grained manipulations. A major aim in the research on linguistic effects on decision making should thus be the development of appropriate within-subject experimental paradigms. To this end, the circumstances under which effects present in between-subject designs are retained when participants repeatedly perform variations of the same task should be investigated.

Several other research questions are raised by our results. One issue are possible differences between bilingual communities accustomed to varying amounts of language switching (such as Turkish immigrant communities in Germany, or Hispanic communities in the US). Moreover, our data point toward a possible asymmetry between switching into the native and into a foreign language, which might be due to an easier return to the native language. Whether this effect will change in groups of more balanced bilinguals, or in bilinguals who live in an FL-immersed setting (i.e. immigrants or exchange students) should be a subject of future studies. Furthermore, it is pertinent to understand whether the reported effects are specific to language switching or can similarly be induced by other conditions requiring raised levels of cognitive control, such as perceptual difficulty (Alter, Oppenheimer, Epley, & Eyre, 2007) or working memory load(Whitney et al., 2008). Finally, as our Study 4 focused on the framing effect, we cannot rule out that general foreign language effects exist for other types of decision patterns, such as those observed for moral decisions (Costa, Foucart, Hayakawa, et al., 2014; Geipel et al., 2015). Future studies should test general and situational language factors mediating other types of irrational behaviors.

5.6. Conclusions

This dissertation work provides insights into cognitive and neuronal mechanisms of visual word recognition in bilinguals and its interaction with non-linguistic processing. We scrutinized how a second language is integrated in the visual word processing system and how bilingualism interacts with other cognitive domains. Specifically, we refine the cognitive and neuronal mechanisms underlying the interaction of first and second language statistics at the sublexical level and provide a novel description of activation propagation on the lexical reading route and from sublexical and lexical representations to language nodes. Moreover, the results on framing provide a show-case for spill-over of cognitive control during language switching to non-linguistic processing. To summarize, this thesis constitute a first step towards a unified neurocognitive process model of visual word processing and non-linguistic decision making that builds on and integrates currently available bilingual and monolingual models.

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7. Appendices