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Weaker Semantic Priming Effects With Number Words in the Second Language of Math Learning

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Bilinguals' exact number representations result from associations between language-independent Indo-Arabic digits ("5"), two verbal codes ("fünf" and "cinq") and a common, largely overlapping semantic representation. To compare the lexical and semantic access to number representations between two languages, we recruited a sample of balanced highly proficient German–French adult bilinguals. At school, those bilinguals learned mathematics in German for 6 years (LM1) and then switched to French (LM2) in 7th grade (12 years old) until 13th grade. After the brief presentation of primes (51 ms) consisting of Indo-Arabic digits or number words in German or French, an Indo-Arabic digits target had to be read in either German or French in an online study. Stimuli were numbers from 1 to 9, and we varied the absolute distance between primes and targets from 0 (i.e., 1–1) to 3 (1–4; as in Reynvoet et al., 2002). The priming distance effect (PDE) was used to measure the strength of numerical semantic association. We find comparable PDEs with Indo-Arabic digits and German number word primes, independently from the target naming language. However, we did not find a clear PDE with French number word primes, neither when naming targets in German, nor in French. The weaker PDE from LM2 compared to LM1 primes is interpreted as a weaker lexico-semantic association of LM2 number words. These results indicate a critical role of the LM1 and further emphasize the role of language in processing numbers. They might have important implications for designing bilingual school curricula.

Public Significance Statement

This study demonstrated a cognitive cost for highly proficient bilinguals when processing the meaning of numbers in a second language. The cost was observed even though bilinguals had attended math classes in the second language (French) during 7 school years, following math acquisition in the first language (German) over a period of 6 school years. Our findings indicate that sequential bilingual school curricula imply a cost for processing numbers in the second language. Given the hierarchical nature of math education and its fundamental importance for later academic and professional achievement, this cost should ideally be acknowledged and addressed to assure optimal learning outcomes.

Keywords: numerical cognition, priming distance effect, bilingualism, language of mathematical learning

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Human beings have nonsymbolic and symbolic representations of numerosities. Nonsymbolic number representations (i.e., •••••) are approximate and functional very early in cognitive development (Barth et al., 2003; Halberda et al., 2008; Xu & Spelke, 2000). On the other hand, symbolic representations such as English number words (i.e., "five") and Indo-Arabic digits (i.e., "5") are precise and acquired later in development. The acquisition of number words promotes precise numerical representation as sustained by developmental studies (Negen & Sarnecka, 2009, 2012; Wynn, 1992) and cross-linguistic studies on languages with restricted number words (Frank et al., 2008; Pica et al., 2004; Pitt et al., 2022; Spaepen et al., 2013). Number words' and Indo-Arabic digits'

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semantic representations are associated with common numerical features (e.g., magnitude, order, or parity, Koechlin et al., 1999; Marinova et al., 2021). Moreover, the development of number semantic representations predicts later mathematic performances both when considering number words (Desoete et al., 2012; Lê & Noël, 2021; Major et al., 2017; van Marle et al., 2014) and Indo-Arabic digits (Göbel et al., 2014; Schneider et al., 2017). Yet, for bilinguals different sets of number words exist in their respective languages, in contrast to Indo-Arabic digits, which are in use across numerous languages and writing systems (Ifrah & Bellos, 2000). Therefore, bilinguals might show different strengths of association between number words of the different languages, Indo-Arabic digits, and their semantic representations. The strength of association possibly depends on the language of mathematical education and might in turn influence mathematical performances (Van Rinsveld et al., 2017). The present study aims to investigate how the language of learning mathematics (LM) shapes lexical and semantic representations of number words of proficient bilinguals, which is of particular interest for bilingual school curricula.

Bilingual Arithmetic and Transcoding

Studies on bilinguals solving arithmetics or doing transcoding tasks (i.e., involving the conversion of a number between either its nonsymbolic, verbal, or visual form) highlight the importance of the language in which mathematics is learned. Those studies reveal a cognitive cost, hence a worse performance on the same task when done in the less dominant language, or the language not used for formal math acquisition or ad hoc arithmetic training. This cost can be measured as slower reaction times or more errors. In a seminal study by Spelke and Tsivkin (2001), bilingual Russian dominant (L1) participants who later learned English (L2) were trained to solve arithmetic either in their L1 or L2. A consequent test conducted in the L1 and L2 resulted in a cost for solving arithmetics in the untrained language which was independent of the testing language (i.e., L1 or L2). Therefore, independently from language dominance (i.e., L1 or L2), participants performed worse when switching between learning and testing language: a language switching cost (LSC). LSCs have been measured behaviorally (Dehaene et al., 1999; Hahn et al., 2019; Saalbach et al., 2013; Volmer et al., 2018), as well as with functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) neuroimaging methods indicating different brain activity when solving problems in an untrained language compared to the trained one (Grabner et al., 2012; Venkatraman et al., 2006). Hence, LSC might have important consequences on how bilinguals learn language-dependent arithmetic facts. Bernardo (2001) investigated students with L1 dominant Philippino, who learned mathematics in English at school, indicating a cost for solving arithmetic in Philippino compared to English. These results suggest a critical role of the language of LM for arithmetic facts consolidation. Solving arithmetic in the L1 compared to a different LM also elicits distinct EEG responses (Salillas & Wicha, 2012, but see Cerda et al., 2019; Martinez-Lincoln et al., 2015). Hence, independent of the L1, those studies suggest a benefit for solving arithmetic in the LM.

The language-related cost arising during arithmetic might partially originate in the more elementary process of transcoding, which is thought to be a subprocess involved in solving arithmetic. For example, when solving "$7 \times 6 = ?$," the results could involve the passage from a visual to a verbal code, as suggested by correlations between reaction times to solve arithmetic and transcode numbers (Clayton et al., 2020; Steiner et al., 2021). Furthermore, both arithmetic and transcoding tasks reveal costs when performed in the less dominant or untrained language. For bilingual participants who followed the Luxembourgish school system where mathematics is taught first in German for 6 years (LM1) and then in French for 7 years (LM2), slower response times and more errors for complex arithmetic are found for LM2 compared to LM1, even in adults (Van Rinsveld et al., 2015). The LM2 cost for French was further replicated in a second cross-sectional study for the more elementary task of transcoding two-digit Arabic numbers, also until adulthood (Lachelin et al., 2022; see also Garcia et al., 2021 for complementary results in a meta-analysis).

In sum, these studies reveal language-specific costs during arithmetic and transcoding tasks in bilinguals. However, it remains unknown from which specific processing level those costs arise when bilinguals are dealing with numbers. For example, in the case of German (LM1) and French (LM2) bilinguals, the cost in transcoding might be explained uniquely by lexical retrieval, that is, retrieving that "5" is "fünf" would be faster than "cinq." Or additional costs might be due to later weaker semantic associations. To address this open question, we used the priming distance effect (PDE) as an experimental paradigm (see section Distance Effect) and relied on the triple code model (TCM) as a theoretical framework (see section Bilingual Triple Code Model) to precisely locate the levels of language-specific costs during number processing in highly proficient bilinguals (see section Heterogeneity in Bilingualism).

Distance Effect

The distance effect refers to a decrease in participant's performance when required to compare two numbers as the absolute difference between two numbers is reduced (e.g., 5 vs. 6 compared to 5 vs. 9). It is commonly used to assess the semantic relation between numbers (Moyer & Landauer, 1967) and reveals activation of number semantics more generally. The distance effect can also be observed in priming paradigms: the PDE. In this paradigm, the prime modulates reaction times as a function of the distance between prime and target, so that closer numerical distances (i.e., prime = 4, target = 5) elicit faster responses than distant pairs (i.e., prime = 2, target = 5; Koechlin et al., 1999; Naccache et al., 2002). Developmentally, PDEs with Indo-Arabic digits as primes are already found in first graders and remain stable for older age groups (Reynvoet et al., 2009). Remarkably the PDE can be elicited from primes presented as Indo-Arabic digits as well as number words (Reynvoet et al., 2002), thus allowing to test the semantic activation with number words in different languages. Despite the use of very fast and masked primes (i.e., 43 ms), these modulate both reaction times and cerebral responses as a hallmark of a distance effect (Koechlin et al., 1999; Naccache & Dehaene, 2001; Notebaert et al., 2010). PDEs are also observed when measuring voice onset times (VOT) in experiments where the targets have to be named (Reynvoet & Brysbaert, 1999), thus allowing to compare responses in different languages with the same paradigm.

To test number semantic associations in multilinguals' different languages, number word translation PDE paradigms have been used. Thus, Duyck et al. (2008) investigated Dutch (L1)–English (L2)–French (L3) speakers with L2 number word primes and L1 or L3 number word targets. The task was either to read the targets in the language they were written in (within language) or to translate them. When the same numerosity was presented as prime and target (i.e., in repetition priming trials, two in the examples) mean VOTs were faster than with nonrepeated primes with both forward (L1 targets translated to L3, i.e., prime = "two," target = "twee," response = /deux/) and backward translation (L3 to L1, i.e., prime = "two," target = "deux," response = /twee/). Moreover, PDE was observed when naming in L1 (both with L1 and L3 target number words, hence after a backward translation, i.e., prime = "two," target = " vijf" or "cinq," response = /vijf/ or /vijf/). In contrast, no PDE was observed when naming in L3 (both with L3 and L1 targets, hence after a forward translation, i.e., prime = "two," target = "viijf" or "cinq," response = /cinq/ or /cinq/). The interpretation was that backward translations have a stronger lexico-semantic association than forward translations. However, this study did not allow to compare lexico-semantic associations within each language, since the language of prime and target number words systematically differed. Duyck and Brysbaert (2002) partially addressed this question by presenting Dutch (L1)–French (L2) bilinguals with Indo-Arabic digits primes and L1 or L2 number word targets which had to be named in the presented language or translated. Again, PDEs were observed when naming in L1 (both with L1 and backward translated L2 target number words, i.e., prime = 2, target = "vijf" or "cinq," response = /vijf/ or /vijf/) but they were absent in the group instructed to name in L2 (both with L2 and forward translated L1 target number words, i.e., prime = 2, target = "cinq" or "vijf," response = /cinq/ or /cinq/). Repetition priming, that is, when the prime is the same number as the target, was stronger when targets had to be translated (i.e., prime = 2, target = "twee" or "deux," response = /deux/ or /twee/) than named (i.e., prime = 2, target = "twee" or "deux," response = / twee/ or /deux/).

These studies demonstrate that the PDE paradigm can be used to assess the lexico-semantic associations of numbers in bilinguals. However, they did not probe whether number words in L1 and L2 automatically elicit semantic activations when presented as prime briefly before Indo-Arabic digits have to be named. Furthermore, the participants in the above-mentioned studies were not balanced bilinguals since they acquired the L2 lately (i.e., as 10-year-olds) and L2 was not a language of LM for them.

Bilingual Triple Code Model (BTCM)

The TCM (Dehaene, 1992) synthesizes the neurocognitive modular organization between number words (verbal), Indo-Arabic digits (visual), and abstract semantics. The TCM's verbal code is part of general-purpose language abilities. The transcoding routes between verbal and visual are asemantic according to the TCM, meaning that the access to number's abstract code is not required. However, PDE experiments described previously suggest an automatic semantic co-activation from Indo-Arabic and number word primes. Those experiments also indicate that PDE activation of the semantic representation depends on prime notation (Koechlin et al., 1999). In the original formulation of the TCM (Dehaene, 1992) number semantic is activated only by the most dominant language of bilinguals. However, another possibility is the existence of language-specific parallel, but distinct, semantic associations. In this case, the gradient of semantic activation spread might vary not only with notation but also with the languages of a bilingual.

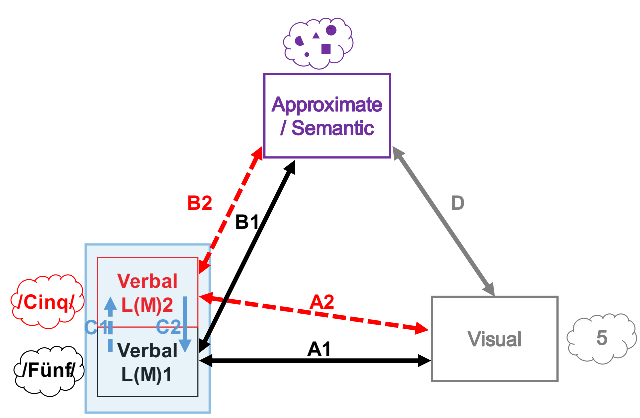
Here, we propose a rewriting of the TCM onto a BTCM, such that each language-specific verbal code would have parallel bidirectional lexico-visual (see A1 and A2 in Figure 1) and lexico-semantic (B1 and B2) associations starting from each language-specific verbal codes (see Figure 1). Within the verbal code, a direct lexico-lexical connection between the language-specific verbal codes would also be available for number word translation (C1 and C2 in Figure 1). From the literature, we know that translation is easier from L2 to L1 (backward) than from L1 to L2 (forward), which is also predicted in the revised hierachical model (Kroll et al., 2010). From this BTCM framework, we can therefore compare each verbal code's specific lexical association, lexico-visual and lexico-semantic association, or activation. Hence, the strength of association of the verbal codes might differ between each of the bilinguals' languages.

The strength of association (dashed compared to full lines in Figure 1) could in part be determined by general language factors such as balanced bilingualism and L2 proficiency (i.e., Garcia et al., 2021). More specific factors affecting the strength of association are the language of (math) training (as for LSC, i.e., Saalbach et al., 2013) or the language of LM (Van Rinsveld et al., 2015). Depending on their specific configurations, these factors and their interactions could lead to weaker associations between verbal, visual, and/or semantic processing levels and entail corresponding costs. Hence, weaker L(M)2 associations are expected for unbalanced bilinguals as well as for bilinguals with low proficiency and/or less math training in L(M)2.

Alternative models accounting for transcoding in bilinguals include a version of the encoding complex model (ECM;

Figure 1

BTCM Representing Lexico-Semantic and Lexico-Visual Associations Between Each Language's Code Represented With Black and Red Arrows



Note. Blue unidirectional arrows indicate translations between the two languages existing for the verbal code: forward translation from L(M)1 to L(M)2 (C1); backward translation from L(M)2 to L(M)1 (C2). Dashed arrows indicate weaker associations compared to full arrows. The arrows correspond to: bidirectional lexico-visual associations with L(M)1 (A1), bidirectional lexico-visual associations with L(M)2 (A2), semantic access from—and to—L(M)1 (B1), semantic access from—and to—L(M)2 (B2), independent semantic access from—and to—the visual code (D). BTCM = bilingual triple code model; L(M)1 = first language (of mathematical) learning; L(M)2 = second language (of mathematical) learning. See the online article for the color version of this figure.

Campbell & Epp, 2004) and a bilingual ECM (Bernardo, 2001). There are three main differences between the proposed BTCM and ECM. First, while for the ECM the strength of associations between formats and languages depends on tasks and training (encoding-retrieval integration), the BTCM introduces age or order of acquisition as a factor such that earlier acquired languages have stronger associations. This point is relevant in practice with regard to bilingual education. Second, the BTCM assumes that both languages are integrated into a single lexicon rather than two separated ones. Third, the ECM does not include translations from one language to another and asymmetries regarding the strength of associations (i.e., Figure 1, C1 and C2). An interesting connectionist model has also been proposed by Duyck and Brysbaert (2004). In this model, each lexicon of the different languages has different degrees of overlap of connections with its corresponding semantic representation, similarly as in the language general bilingual activation model (BIA+) model (Dijkstra & van Heuven, 2002). Note that in these models, differently from the original TCM proposition, the number semantics rather than being a separate system might emerge from the associations between numbers. This is also proposed by the "discrete semantic system," suggesting that the distance effect results from the semantic network between the numbers rather than from a separate semantic system as in the TCM (Krajcsi et al., 2016). Since so many interacting factors might contribute to a language cost, it is particularly important to understand the mechanisms and relevance of language proficiency in bilinguals.

Heterogeneity in Bilingualism

Bilinguals[1] represent more than half of the world's population (Grosjean, 2008). They are proficient in two languages, an L1 and an L2, whose configurations can be very heterogeneous across subjects. For example, L1 and L2 proficiency can range between balanced and unbalanced bilinguals, while L2 proficiency can range between high and low (de Groot, 2011). The L2 proficiency depends on different factors such as the age of acquisition (AoA), language exposure, or L1 and L2 linguistic similarities, which in turn influences the organization of the brain (Del Maschio & Abutalebi, 2019; Hernandez, 2013; Klaus & Schriefers, 2019). L1 and L2 are activated in parallel during comprehension and production (Colomé, 2001; Dijkstra, 2005; Marian & Spivey, 2003). This concurrent activation is controlled by top-down prefrontal inhibitory mechanisms (Abutalebi, 2008; Green, 1998). The strength of top-down inhibition mechanics depends on both L2 and L1 proficiency, such that balanced bilinguals should have comparable inhibition strengths for both L1 and L2 (Costa & Santesteban, 2004), while bilinguals with high L2 proficiency have a stronger inhibition than those with a low L2 proficiency (de Groot, 2011). In addition, differences between L1 and L2 strength of activation might also occur at different language processing stages such as lemma, lexical, or semantic (Kroll et al., 2010). On a theoretical level, weaker L2 compared to L1 activations affecting those different stages are predicted by several psycholinguistic models of bilingual language production and comprehension.

In sum language, proficiency is an important marker of how languages are stored in the bilingual's brain. The ideal sample to study (numerical) cognition in bilinguals is thus composed of balanced, highly proficient bilinguals who have formally acquired both languages in school and who have grown up in an environment systematically exposing the individuals to both languages in a similar manner.

Present Study

With the present study, we aim to measure lexical and semantic access from number words in a balanced bilingual sample that sequentially acquired mathematics in a first language (LM1) and then in a second language (LM2). We sampled adults who followed the Luxembourgish public schools where mathematics is learned in German (henceforth LM1) from first until sixth grade (about 12 years old). From seventh grade until the end of obligatory school (19 years old) the language to learn mathematics switches to French (henceforth LM2), thus resulting in highly proficient German–French bilinguals (Ministère de l'Éducation Nationale, 2022). To measure both lexical retrieval and semantic access from number words we implemented a PDE paradigm as in Reynvoet et al. (2002), using German and French number words as primes and Indo-Arabic digits as targets. Number words have a high degree of semantic overlap across languages (i.e., magnitude, order, or parity). Visual Indo-Arabic digits constitute an additional association with both L1 and L2 number word lexicons and semantics. This allowed us to measure the strength of priming through number words in both languages on Indo-Arabic digits, which can also be named in both languages. We defined the following hypotheses:

> *Hypothesis 1:* We expected an LM2 cost for lexical retrieval, with slower VOTs for Indo-Arabic digit naming in the LM2 than in the LM1, as suggested by previous studies (Garcia et al., 2021; Lachelin et al., 2022).
>
> *Hypothesis 2:* We expected weaker LM2 lexico-semantic associations, which would be reflected by weaker PDEs with LM2 than LM1 number word primes (Dijkstra & van Heuven, 2002; Kroll et al., 2010).

The study was implemented on Labvanced, a web-based platform (Finger et al., 2017). Previous replications of studies on numerical cognition have shown that even masked priming studies can be implemented on web-based platforms (Kochari, 2019).

Method

Participants

A total of 39 participants completed the experiment in exchange for a €5 voucher. Seven participants were excluded because French was reported as the most proficient language. None of the participants reported antecedents of dyscalculia, dyslexia, or epilepsy. Hence, the final sample was composed of 32 participants ($M_{\text{age}} =$ 23.6 years, $SD = 6.1$ years, gender reported: 26 females, six males, zero other). The sample reflected Luxembourg's multilingualism, with the participants reporting knowing on average $M =$ 4.8 (0.8) languages and all participants speaking Luxembourgish, German, French, and English.

The sample's average AoA and frequency of use are described in Table 1 for the five most frequently reported languages. Note that

[1] Herein we will use and describe the specific case of bilingualism which is a subgroup for the more general term multilingualism (proficiency in multiple languages).

Table 1
AoA (Indicated in Years) and Frequency of Use of the Language (Frequency of Use)

Metrics	Luxembourgish	German	French	English	Portuguese
AoA	2.13 (2.27); 13[a]	4.9 (2.10); 2[a]	7.06 (1.72); 0[a]	12.72 (1.46); 0[a]	0.7 (1.06); 6[a]
Frequency of use	4.87 (0.5)	4.09 (0.69)	3.87 (0.75)	3.74 (0.85)	4.9 (0.32)
N	31	32	32	32	10

Note. AoA is reported with responses 0 included. Frequency of use: 5 = *daily*, 4 = *weekly*, 3 = *monthly*, 2 = *yearly*, and 1 = *never* (1 was not answered for these languages). *N* = number of participants reporting those languages. Standard deviations in parenthesis. AoA = age of acquisition.
[a] Number of participants with response = 0.

linguistically speaking, Luxembourgish can be considered a German dialect (Martini, 2021), with number words being orthographically, phonologically, and morphologically very similar to German.

The specific AoA of language in which mathematics was learned was reported earlier for German, 6.4 (1.7) years old than for French, 12.0 (2.3) years old. This is fully in line with the Luxembourgish school curriculum where all topics are taught in German from first (6 years old) to 10th grade, except for mathematics, which is taught in French from seventh grade onwards (12 years old). Overall, 25 participants reported using their most proficient language (German/Luxembourgish for the majority) to solve different types of arithmetic problems. From 11th grade onwards, all topics are taught in French. This results in highly proficient German–French bilinguals (Ministère de l'Éducation Nationale, 2022). Therefore, in the following analyses, the language of LM will be considered as a factor, with German being the first language of LM1 and French the second (LM2).

The Ethical Review Panel approved the experimental protocol at the University of Luxembourg (ERP 21-005 OnBiNNPri). Before undertaking the experiment, participants gave informed consent.

PDE Task

Participants were presented with a masked priming task similar to the one used by Reynvoet et al. (2002). Both masks and primes lasted 51 ms. The masks were controlled to visually overlap the longest prime (i.e., "SIEBEN"). After the backward mask, the target was presented for 2,500 ms, at which the microphone recording started (see Figure 2). The participant's task was to name the target, which was an Arabic digit for all trials. Prime awareness was asked at the end of the study but due to a technical error, this response was not recorded.

The masks and stimuli were in black and were programmed to appear in the center of a gray screen. All stimuli were presented within a 6 × 2 visual angles text box in the middle of the screen. Visual angle self-calibration was possible thanks to Labvanced's built-in feature requiring the participants to adjust the distance from the screen and calibrate the screen size with a standard-sized credit card at the beginning of the experiment. The participant saw an adjustable rectangle on the screen that could be adjusted with the mouse to match the size of the card.

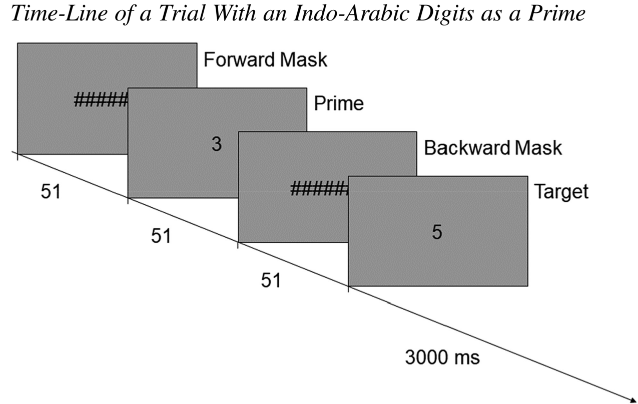
Participants' verbal responses to the targets, measured by the VOTs serve as the dependent measure. The VOT were encoded using CheckVocal (Protopapas, 2007) by automatic voice onset detection. Then, an external experimenter, naïve to both the hypothesis and primes, visually and auditorily checked each recording. Manual adjustments were made whenever necessary. For instance, to correct the VOT for number words starting with fricatives (i.e., /vier/ or /deux/), and to identify any additional noise (e.g., mispronunciations, recording errors, etc.).

Stimuli

All the stimuli (targets and prime) were numbers ranging between 1 and 9, depicted as Indo-Arabic digits or number words. Primes varied in notations: Indo-Arabic digits (i.e., 5), German number words (i.e., FÜNF), and French number words (i.e., CINQ). The targets were always Indo-Arabic digits. Thus, both languages were retrieved from the same Indo-Arabic digit depending on the experimental condition. The distances between prime–target pairs (i.e., absolute(target − prime)) were restricted to 0, 1, 2, and 3. That is, the distance 0 represents repetition priming since the same number value is presented as prime and target.

To avoid statistical prediction strategies each Indo-Arabic digit from 1 to 9 was equally frequent within each condition's target. To achieve this we had to balance the prime–target pairs, for example, for the items corresponding to the distance 1, the prime–target pairs 2–1 and 8–9 were presented twice, see Table 1 in the online supplemental materials. Additionally, 18 trials with a "filler" prime (i.e., ######) were added to have a baseline of nonprimed number naming. In sum, each of the two conditions contained 234 experimental trials (72 pairs with prime = number word German, 72 prime = number word French, 72 prime = digit, 18 filler trials). The different notation prime and target pairs were randomly

Figure 2
Time-Line of a Trial With an Indo-Arabic Digits as a Prime



Note. Other trials included German or French number words as primes. The participant's task was to name the target, which was always an Indo-Arabic digit, in either German or French (blocked).

presented within each condition, while naming languages were blocked.

Procedure

Participants were recruited via mailing lists and social media targeting university students with at least 10 years of schooling in Luxembourg by sharing a link to the experiment hosted on the web-based platform Labvanced (Finger et al., 2017). Hence, the experiment ran on the participant's personal computers at home. The participants were required to be in a quiet room where they would not be disturbed or distracted for the duration of the experiment. Each participant was randomly assigned to a German or French language starting condition (15 participants started in German, 17 in French). Before the task, the participant answered a short 13-item questionnaire about demographics, self-reported language use, and language for number processing (described above). The questionnaire was followed by written instructions and translated according to the starting language condition. This manipulation was done to balance the language mode before starting the experiment across the sample (see Grosjean, 2001). Then the task started with the condition that all targets had to be named in the starting language. Between each language block, participants could take a short break. The same stimuli set (prime–target pairs) was presented for both blocks, but their order of presentation was randomized before each block. The experiment lasted about 30–35 min. At the end of the experiment, each participant could indicate their contact information to receive their compensation.

Data Analyses

Data were analyzed using linear mixed models (LMMs). All analyses were done with R (RStudio Team, 2020) and the following packages: For the LMMs afex (Singmann et al., 2020), which relies on lme4 (Bates et al., 2015). Follow-up analyses were computed with emmeans (Lenth, 2021), and graphs were drawn with ggplot2 (Wickham, 2016). VOTs were used as a dependent variable.

Transparency and Openness

Data and R scripts to reproduce the results are available at: https://osf.io/j8vzu/.

Results

Task Descriptive

From the 32 participants, a total of 14,972 VOTs were measured (a few participants who quit the experiment at a maximum of 32 trials before the end of the experiment due to program error were included). VOTs were filtered according to the three following criteria: First trials marked as mispronunciations, failed or unintelligible recordings (0.59% of the total). From these (i.e., 88/14,972 trials), only 14 were mispronunciations and three were responses in English, hence too few for conducting further meaningful analyses on accuracy. Second, by applying highpass (300 ms) and lowpass (1,500 ms) filters on the VOT (0.27%). Third, we excluded each VOT exceeding 3 *SD*s from individual means to remove outliers (1.50%). In sum, 2.36% of the initial total trials were filtered out (ending with 14,619 trials to analyze).

Filler Prime

We analyzed the trials with the "filler" primes (i.e., ######), that is the trials corresponding to digit number naming without any number priming. For these trials, we observed faster VOT in the block where the target had to be named in German, 642 (89) ms, than in French, 665 (101) ms, paired t test: $t(31) = -3.07$, $p = .004$. This result indicates a cost for lexical access from Indo-Arabic digits to the corresponding number word in the LM2 (French) compared to the LM1 (German).

LMM

LMMs were applied with: distance (0, 1, 2, 3), prime notation (digit, German number word, and French number word), and target naming language (German or French) as fixed factors. Random slopes and intercepts were modeled to adjust for differences between the different target's number word length in both languages. Random intercepts for each subject were also included in the model to take into account individual differences in VOT. The following maximal model (A) was defined a priori (Barr et al., 2013). Because the model (A) did fit and did not present any problems such as singularity we did not need to select or remove terms. All degrees of freedom of the following analyses were obtained by the Satterthwaite approximation method, comparing the full model against the model without the effect (Singmann et al., 2020). The R syntax of the main model was as in (A):

$$\text{(A) VOT} \sim \text{Distance} \times \text{Prime Notation} \times \text{Naming Language} + (\text{Naming Language}|\text{Target}) + (\text{Naming Language}|\text{Subject}).$$

The main LMM resulted in a main effect of distance, $F(3, 13382.14) = 140.07$, $p < .001$, prime notation, $F(2, 13382.14) = 70.94$, $p < .001$, and target naming language, $F(1, 17.06) = 6.10$, $p < .05$. Prime notation interacted with distance, $F(6, 13382.14) = 9.83$, $p < .001$, and with target naming language, $F(2, 13382.14) = 3.06$, $p = .05$. Since the main LMM showed a main effect of prime notation, we decided to conduct two separate LMMs for digits and number words. Separate analyses are also justified theoretically since both notation formats have different underlying cognitive processes (see Reynvoet et al., 2002). The same random effects by targets and participants were maintained as for the main LMM as described above. Table 2 depicts the VOT for each distance by prime notation and target naming language.

LMM by Prime Notations

Indo-Arabic Digits

The LMM applied on the condition with Indo-Arabic digits as primes was as in formula (A), but without the main effect of prime notation format. This LMM yielded a main effect of the target's naming language, $F(1, 19.90) = 6.76$, $p < .05$, with slower VOT when naming the targets in French than in German. This indicates a lexical retrieval cost for the LM2 compared to the LM1, as it was already visible in the filler prime condition. Furthermore, we also found a significant main effect of

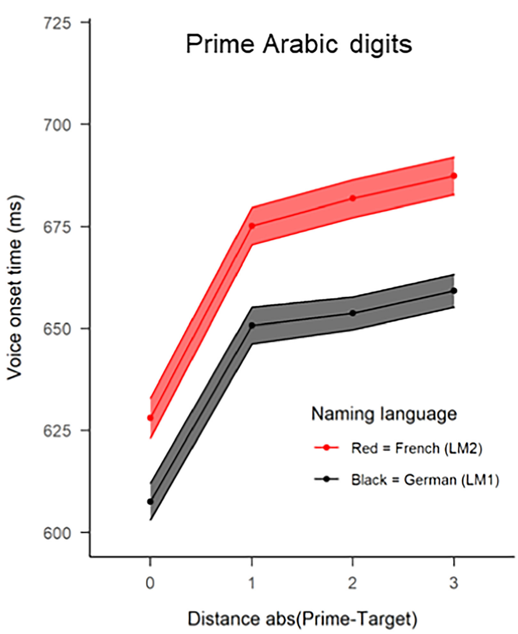
Table 2
VOT for Each Distance and Different Primes

	Prime's notation								
	Digit		NW German		NW French				
	Target's naming language							#######	
Distance	German	French	German	French	German	French		German	French
0	607 (106)	628 (116)	640 (110)	670 (120)	652 (101)	657 (118)	No prime condition	642 (60)	666 (65)
1	650 (106)	675 (107)	662 (103)	687 (104)	668 (96)	689 (116)			
2	653 (95)	681 (109)	670 (104)	694 (107)	664 (99)	687 (108)			
3	659 (95)	687 (109)	671 (103)	698 (105)	667 (99)	695 (111)			
M	642 (103)	668 (113)	661 (105)	687 (110)	663 (99)	682 (114)		642 (60)	666 (65)

Note. Average VOT in milliseconds (*SD* in parenthesis) from data aggregated by distance, prime notation, and target number naming language. VOT = voice onset time; NW = number words.

distance, $F(3, 4420.31) = 106.69$, $p < .001$. Post hoc pairwise decomposition indicated first a significant repetition priming effect, as reflected by faster VOT for the distance 0 (i.e., same prime and target) than distance 1, $t(4420.23) = -12.84$, $p_{\text{holm}} < .001$, estimate $= -44.81$, $SE = 3.49$, Holm correction applied. Second, post hoc analyses revealed faster VOTs for the distance 1 than 3, $t(4420.41) = -3.18$, $p_{\text{holm}} < .01$, estimate $= -11.13$, $SE = 3.50$, yielding a classical PDE. The PDE indicates that shorter distances between prime and the targets facilitated the naming of the targets, which is explained by the prime's semantic processing (see Figure 3).

Figure 3
VOT (in Milliseconds) When Presenting Primes as Digits



Note. Black lines illustrate VOTs when targets are named in French, red (light gray) lines refer to German. The horizontal axis represents the prime–target distance 0, 1, 2, and 3. Ribbons represent standard errors. VOT = voice onset time; LM1 = first language (of mathematical) learning; LM2 = second language (of mathematical) learning; abs = absolute. See the online article for the color version of this figure.

Number Words

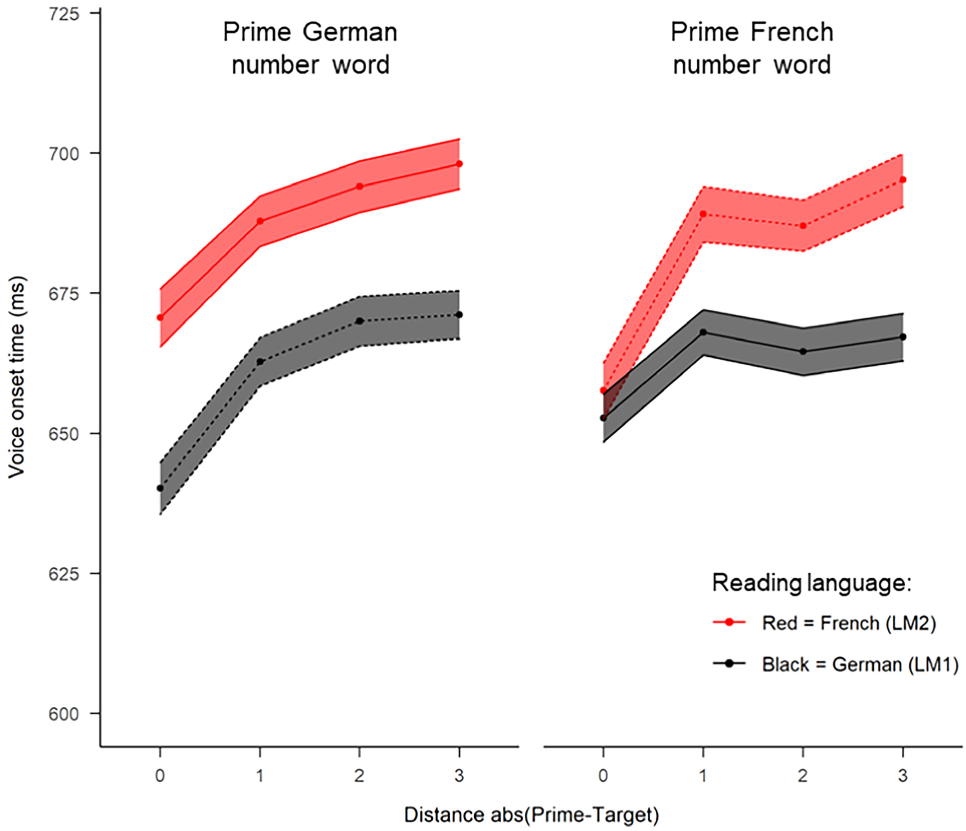
The LMM in (A) was applied to number words, therefore including prime notation as a fixed factor with two levels (German number words, French number words). The LMM resulted in the main effect of the target naming language, $F(1, 15.70) = 5.43$, $p < .05$, indicating a lexical cost for naming number words in French compared to German. Results also showed a main effect of distance, $F(3, 8884.23) = 52.01$, $p < .001$. Furthermore, the two-way interaction between prime notation and target naming language was significant, $F(1, 8884.22) = 5.47$, $p < .05$. Critically, the three-way interaction between distance, prime notation, and target naming language was also significant, $F(3, 8884.21) = 3.31$, $p < .05$.

Post hoc decomposition of the three-way interaction was performed. The results show a repetition priming effect between all prime notations (number words in German and French) in combination with all target naming languages (German and French). That is, significant repetition priming (i.e., distance 0) occurred from German prime number words to targets to be named in German, $t(8884) = -4.43$, $p_{\text{holm}} < .001$, estimate $= -21.75$, $SE = 4.91$, and in French, $t(8884) = -3.60$, $p_{\text{holm}} < .001$, estimate $= -17.93$, $SE = 4.98$. Furthermore, repetition priming was also observed from French prime number words to targets named in German, $t(8884) = -3.01$, $p_{\text{holm}} < .01$, estimate $=$ 14.74, $SE =$ 4.90, and in French, $t(8884) = -6.72$, $p_{\text{holm}} < .001$, estimate $= -33.13$, $SE = 4.93$, thus showing repetition priming from number words in German and in French, independently from the target naming language.

For the PDE, we compared the distances 1–3 for each prime's notation and each target's naming language. These contrasts indicated a PDE for German number words, which was nearly significant when naming the targets in German, $t(8884) = -1.88$, $p_{\text{holm}} = .06$, estimate $= -9.21$, $SE = 4.90$, and significant, when naming in French, $t(8884) = -1.95$, $p_{\text{holm}} = .05$, estimate $= -9.68$, $SE = 4.96$. Critically, however, in comparison, the number PDE effect was absent when French number words were used as primes, both when targets were named in German, $t(8884) = -0.03$, $p_{\text{holm}} = .97$, estimate $= -0.15$, $SE = 4.93$, and in French, $t(8884) = -1.14$, $p_{\text{holm}} = .25$, estimate =

Figure 4

VOTs (in Milliseconds) When Presenting German Number Word (Left Panel) and French Number Words (Right Panel) as Primes



Note. Black lines illustrate VOTs when targets are named in French, red (light gray) lines refer to German. The horizontal axis represents the prime–target distance 0, 1, 2, and 3. Ribbons represent standard errors. Segmented lines represent crossed language conditions (i.e., when the prime differs from the target naming language). VOTs = voice onset times; LM1 = first language (of mathematical) learning; LM2 = second language (of mathematical) learning; abs = absolute. See the online article for the color version of this figure.

−5.64, $SE = 4.95$ (see Figure 4). Hence, independently of the naming language, priming with German number words elicited a PDE, while priming with French number words did not. In other words, number words in French showed weak lexico-semantic access compared to number words in German.

Discussion

The current study aimed to compare the lexical and semantic associations of single-digit numbers in bilinguals. To this aim, we tested highly proficient balanced German–French adult bilinguals who followed a school curriculum where the language for LM switches from German (LM1), that is, 6–12 years old, to French (LM2) at seventh grade, that is, 12–19 years old. Participants performed a number naming task in a semantic masked PDE design (Reynvoet et al., 2002) while their VOTs to the targets were measured. The target retrieval language (German vs. French), the semantic distance between numbers (0, 1, 2, 3), as well as the prime notations (no prime vs. digits vs. French number words vs. German number words) were manipulated within-subject. PDE was used as an estimate of the prime's semantic activation.

The overall results of the LMM analysis show the following pattern. First, the VOTs were slower when naming Indo-Arabic digits in French (LM2) than in German (LM1). This LM2 cost of about 20 ms is already significant in the no prime trials (i.e., "######") and overall in all prime notations. Since this general LM2 cost is not affected by the prime notation, we interpret it as arising from a lexical retrieval stage. Second, we found a PDE for Arabic digit primes: Closer primes and targets elicited faster VOTs than distant pairs. On a methodological level, this PDE confirms the validity of the measures from the online platform (Kochari, 2019). Theoretically, since the PDE is found for both target naming languages, this result indicates that the lexico-semantic association activated by Indo-Arabic digits is language-independent, as predicted by the triple code model (Dehaene, 1992). Third, independently from the prime's notations, repetition priming trials (i.e., when the target and prime represent the same numbers, distance = 0) elicited faster VOTs than distance 1. We interpreted this result as strong lexico-lexical associations between Indo-Arabic digits and both of their verbal phonological German and French correspondents. Note that the repetition priming with Indo-Arabic digits might also be explained by the low-level full visual overlap between prime and target, however, for number word primes, it must tap into higher-level cognitive processes. Hence, an important interpretation from the repetition priming is that both LM1 and LM2 number words are associated at a lexical level with their exact Arabic digit match. The repetition priming worked for forward (i.e., LM1 prime number words to LM2 target naming language) and backward crossed prime-naming languages (i.e., LM2 to LM1), indicating a common process for both languages. Fourth, and critically, while trials primed with number words in German (LM1) resulted in a PDE, those with number word French (LM2) did not. These findings indicate weaker lexico-semantic associations from LM2 number words compared to LM1. Since LM2 number words were effective primes for the repetition priming but not for PDE, this suggests that LM2 number words are effectively processed at the lexical level, but have weak lexico-semantic associations with neighboring numbers. In a nutshell, we thus observed a lexical retrieval cost for LM2 (French) when naming Arabic digit targets, and an additional cost in lexico-semantic access from LM2 number word primes, compared to LM1 (German).

Lexical Retrieval Cost

The lexical retrieval cost for naming Indo-Arabic digits in the LM2 replicates and extends previous findings. Similar LM2 costs were for example observed during arithmetic problem solving (Van Rinsveld et al., 2015) and two-digit number transcoding tasks (Lachelin et al., 2022) in a comparable sample that followed the Luxembourgish educational system. In general, those results align with psycholinguistics investigations indicating slower recognition and production for later learned words in object naming, word naming, and lexical decision tasks (i.e., Hirsh et al., 2003). Theoretically, the lexical LM2 cost might arise from language competition with the LM1 during the lexical retrieval stage. Since Indo-Arabic digits are language nonspecific, they might have nonselective lexical access. Therefore, a digit possibly activates both languages' lexical correspondents. During this lexical competition, the LM2 cost would result from weaker lexical associations than present in LM1 number words. This lexical cost is predicted from multiple theories on bilingualism, such as the inhibition control hypothesis (Green, 1998), the revised hierarchical model (Kroll et al., 2010), and the BIA+ (Dijkstra & van Heuven, 2002). This prediction is also made by models specific to numerical cognition such as the bilingual ECM (Bernardo, 2001), predicting stronger verbal codes in the language used for practicing arithmetic. Finally, regarding the proposed BTCM, it means that the weights of visual–verbal associations are weaker with the LM2 than with LM1 (see Figure 1, arrows A2 and A1, respectively).

Since number words are orthographically and phonologically longer in German than in French (see Table 2 in the online supplemental materials), it is unlikely that this cost is due to the number words length effect (N. C. Ellis & Hennelly, 1980). In addition, more transparent grapho-phonologically languages such as German have in general a more accentuated word length effect (Ziegler et al., 2001; Ziegler & Goswami, 2005). Hence, the lexical cost observed for French (as LM2) compared to German (as LM1) might even be underestimated. Note that additionally, compared to monolinguals, this cost might add up to an already slower lexical retrieval in L1 for bilinguals (i.e., in picture naming tasks: Ivanova & Costa, 2008).

Lexico-Semantic Cost

We interpret the absence of PDE when priming with LM2-French number words compared to LM1 as elicited by an LM2 lexico-semantic cost. The cost appears at a later semantic association stage since priming LM2 number words elicited a repetition priming (i.e., "cinq" facilitated the naming of "5"), indicating LM2 number words were processed at an earlier lexical level. This cost is not appearing at target's lexical retrieval level since a PDE is observed with targets that are named in French and are being preceded by German (LM1) number word primes (i.e., "vier" facilitated the naming of "5" as /cinq/). The presence of repetition priming in both languages but the absence of PDE selectively in the LM2 brings to the conclusion that number words prime's were identified in both languages speaking against a notation effect but rather to the strength of quantity activation (see Koechlin et al., 1999).

Our findings do not appear to align directly with a recent EEG study on bilingual arithmetic verification tasks in English and Spanish, which revealed a similar ERP (i.e., N400, marking semantic processing) for both languages (Cerda et al., 2019). However, the sample's language profile differed from the present study, as L2 was acquired very early (between 0 and 5 years) in comparison to the average 7 years of the present sample. Finally (Martinez-Lincoln et al., 2015) observed equivalent N400 peaks between mathematics performance in later and early learned languages when this was also the teacher's teaching language. This finding suggests the existence of late plasticity for arithmetic memory networks in specific cases, which might also exist for numbers. On the other side, weaker LM2 lexico-semantic associations fit with fMRI studies indicating more brain areas for solving arithmetics in the LM2 (Lin et al., 2019; Van Rinsveld et al., 2017; Wang et al., 2007). More extensive brain activation patterns are hence interpreted as more effortful and less efficient processes. Finally, the present study extends previous results concerning the PDE in bilinguals, such as Duyck and Brysbaert (2002) or Duyck et al. (2008) in that we found a cost with LM2 number word primes. Yet, it differs in that our experiment was designed to measure semantic mediation during number naming, rather than during translation. In addition, the task-relevant stimuli (i.e., primes) of the present study were Indo-Arabic digits, which are language-independent instead of language-dependent number words.

Weaker lexico-semantic associations for L2 fit with general psycholinguistic and specific numerical cognition models of bilingualism. For example, this prediction is made by the revised hierarchical model (Kroll et al., 2010), or the BIA+ (Dijkstra & van Heuven, 2002) and the integrative multilink model (Dijkstra et al., 2019). Specific cognitive models for bilingual numerical cognition also predict weaker lexico-semantic association in the L2 (Duyck & Brysbaert, 2004). However, the bilingual ECM does not predict weaker lexico-semantic association with the LM2, since it predicts an asymmetry in which the weaker lexical code systematically activates the stronger lexical code, while the present results indicate that the stronger lexical code (LM1) induces stronger semantic activations (Bernardo, 2001). Finally, regarding the proposed BTCM (see Figure 1), it would mean that in addition to the lexical association, the verbal lexico-semantic associations from number words are also weaker for LM2 than LM1 (arrows B2 and B1, respectively).

Possible Sources of the LM2 Cost

Cognitive models can provide an approach to explain the LM2 lexical and semantic cost. For example, connectionist models of bilingualism like the BIA+ (Dijkstra & van Heuven, 2002) and lately multilink (Dijkstra et al., 2019) posit the existence of lexico-semantic nodes and connections which might vary in strengths. This theory fits the present study's result that number words would have weaker lexico-semantic connections in the LM2 than in the LM1. However, regarding the source of weaker lexico-semantic LM2 associations, we can only speculate. We suggest hence three potentially complementary accounts: AoA, home language (HL), and bilingual word reading.

First, the general and mathematic-specific (i.e., LM) language AoA is earlier for German than for French in our sample. The specific AoA of mathematical learning corresponds to the age at which mathematics is learned at school: from first grade in German (LM1) and from seventh grade in French (LM2). This corresponds to a strict definition of AoA, that is, an "intensive, systematic, and maintained exposure to his/her new language" (Kovelman et al., 2008, p. 204; see also A. W. Ellis & Lambon Ralph, 2000). Earlier AoA has neurocognitive effects and shapes the neuronal correlates of language and processes related to language. From a neuroscientific perspective, these differences are reflected in the recruitment of more brain regions when solving arithmetic in the L2 than the L1 (Martinez-Lincoln et al., 2015; Wang et al., 2007). Specifically, in a comparable sample more extensive brain activations for LM2 than LM1 arithmetic were also found (Van Rinsveld et al., 2017). A larger brain activation pattern could reflect less optimized cognitive networks when solving arithmetic in L2 or LM2. The weaker lexico-semantic LM2 association might therefore be explained by later AoA. Note, that language general vocabulary acquisition and math-specific vocabulary (i.e., number words) are confounded in the present design so that it is not possible to disentangle the AoA effect due to general versus math-specific aspects. Nevertheless, since math education in LM2 lasts 1 year longer (i.e., 7 years) than in LM1 (i.e., 6 years), we can likely discard an exposure effect (or subjective frequency effect) related to number words in LM1.

Second, language proximity between LM1 and HL could also have played a role: 24 out of 32 participants reported Luxembourgish as the first most proficient language (five as their second most proficient).[2] Hence, Luxembourgish was likely the HL of the present sample. Luxembourgish is linguistically close to German (linguistically as close as the German dialect Bayerisch is to German, see Martini, 2021), which might facilitate the acquisition of German compared to French. The stronger lexico-semantic associations of numbers in LM1 might therefore also have their source in the linguistic closeness between the HL (i.e., Luxembourgish) and LM1 (German). Note that the opposite is also possible: Luxembourgish might hinder French number word's lexico-semantic association. However, it must be noted that Luxembourgish is primarily an oral language; consequently, German written number words are most likely acquired during school. Furthermore, the language of schooling (i.e., LM) is a stronger predictor of Arabic digit naming than HL, as is underlined from studies on bilinguals with Finnish HL and Swedish LM. A series of studies indicated faster Arabic digit naming in the Swedish LM than in Finnish HL, already after 3 years of schooling (Chincotta & Underwood, 1997). Faster digit naming in the LM than in the HL was further accompanied by larger digit spans in LM (Chincotta & Underwood, 1996). Since schooling language seems to be a stronger predictor than HL for Arabic digit naming, it might also be that linguistic proximity of LM1 (i.e., German) with the HL (i.e., Luxembourgish) might have facilitated LM1 lexico-semantic associations compared to (or even hindered) the LM2 association. Linguistic proximity is, however, probably not the only explaining factor since Luxembourgish is mainly a spoken language.

Third, the weak semantic activation by LM2 number words could also arise from reading-related differences as suggested by dual-route reading models (Coltheart et al., 1993). In this account, the LM1 number words would automatically and directly be associated with the semantics, while LM2 number word reading would rely on grapheme–phonological conversion mechanisms. This perspective could explain why LM2 number words elicited repetition priming as lexico-phonological facilitation but no PDE, given the short primes and stimulus onset asynchronies used in this study. However, it could not explain the repetition priming where French number words (i.e., SEPT) facilitated the reading of Indo-Arabic digits (i.e., 7) in German (/sieben/). The latter result indicates that LM2 number words benefit from a higher level of processing than grapheme–phonological conversion, that is, the lexical stage. Moreover, the present graduates from the multilingual Luxembourgish school system have high reading proficiencies in French, particularly for very frequent words, that is, number words. With regards to reading, the language in which reading is first learned (a reading AoA effect), might alternatively explain the weaker lexico-semantic effect. Within this framework, lexico-semantic associations in LM2 would be delayed rather than weaker. If this is the case, longer presentation times or stimulus onset times should result in a PDE in the LM2. Support for a role of reading proficiency comes from previous investigations indicating that Luxembourgish speakers' math performances are mediated by German reading comprehension (Greisen et al., 2021).

In conclusion, weaker LM2 lexico-semantic associations might originate from a combination of earlier AoA of LM1 than LM2 and the linguistic similarity between HL and LM1, as well as the effects of reading. This would then foster stronger lexico-semantic association for LM1 number words than LM2. With regards to the proposed BTCM model, it means that the semantic associations with the language-specific verbal codes depend on similar mechanisms to those at play for general language processes (i.e., AoA and language proximity).

Strengths, Limitations, and Perspectives

The present PDE task and the population recruited for our study have various strengths and limitations regarding the type of stimuli used, their temporality, and the language profiles of participants. Using numbers as stimuli has several advantages in comparison to general words and pictures, which are other stimuli typically used in bilingual investigations. For example, the same visual entry (i.e., Indo-Arabic digits) is used for both languages' lexical accesses. Concerning semantics, numbers have very strong lexico-semantic overlap in different languages,[3] in other words, they refer unambiguously to the same quantity and mathematical properties

[2] The average AoA of for Luxembourgish was 3.8 years old (after excluding 13 reporting 0).

[3] It might be argued that "un" in French is also a pronoun and might therefore be polysemantic.

across languages. Finally, numbers are balanced for the frequency of exposure across languages (Dehaene & Mehler, 1992). However, the use of number words as primes comes with a limit regarding the interpretation of mechanisms related to arithmetic, since arithmetics are usually presented in Indo-Arabic digits (see Cerda et al., 2019).

The very short prime presentation might not have been long enough to reveal a potentially existing but delayed semantic association in LM2 compared to LM1. Indeed, while our results show that lexico-semantic associations cannot be elicited with short LM2 number word primes, the study is not informative about the exact temporality of these associations. Future studies should explore and compare the temporality of both languages' lexico-semantic access to see if the LM2 cost persists. Based on the observation that the PDE is symmetrical for small and large primes, previous PDE studies in monolinguals could exclude the role of counting in the observed response time pattern (Reynvoet et al., 2002). Future studies could nonetheless further explore the possibility that learning the counting sequence contributes to the observed effects in bilinguals. Also note that PDE designs are not suited for correlation, since they are typically observed as group rather than individual effects (see Sasanguie et al., 2011).

The language profiles were quite homogenous from the perspective of the language of LM and HL with 24 over 32 participants reported Luxembourgish as being their most proficient language. Nevertheless, the HL was not directly measured or controlled in this design, since Luxembourgish is linguistically close to German and prevalently oral (as for example Swiss-German). Also, the present multilingual sample reports to be proficient in 4.8 languages, this might have added additional concurrent verbal codes compared to a more exclusive bilingual sample. Notwithstanding the latter limitation, the strong homogeneity of the languages of math learning still makes the present multilingual participants a highly interesting and relevant population for the present research question. Moreover, comparing and understanding the impact of languages of schooling has more practical implications, that is, for school curriculum designs, than knowledge on the effect of HLs.

The present findings might have implications concerning multilingual education since the LM2 cost observed here arises despite 7 years of mathematics in French. Thus, switching language for math instruction in the context of such multilingual education curricula might eventually have detrimental impacts on LMs. This becomes critical when considering that costs even increase for multiple-digit transcoding (Lachelin et al., 2022) and are detrimentally affecting the speed of solving simple and complex arithmetic problems (Van Rinsveld et al., 2015). This could also indirectly be observable in that multilinguals prefer to use their more dominant language to solve arithmetic (Dewaele, 2007; Martini, 2021). Finally, it might also explain the use of lexical retrieval strategies in the LM1 in contrast to alternative strategies in the LM2 (i.e., visuospatial) as suggested by Van Rinsveld et al. (2017). The cognitive cost entailed by sequentially bilingual math curricula should be considered given the hierarchical nature of math education and the strong implications for later individual achievement (Duncan et al., 2007). It might especially increase inequalities by hampering low-achieving math students already struggling in a first language, as the second language is likely to add an additional difficulty toward their mathematical education.

Last, the present result of weaker LM2 lexical and semantic associations in proficient bilinguals might also be important regarding methodological aspects of numerical cognition research. For example, studies using number words might need to be cautious with including multilinguals in their samples, since including LM2 number words could affect the study outcomes.

Conclusion

Our results indicate that proficient bilinguals have two LM2 costs: One in lexical retrieval when naming Indo-Arabic digits and a second due to weaker lexico-semantic activation from LM2 number word primes. This cognitive component must be considered when switching a language of teaching and testing mathematical knowledge. The present results add up to previous studies revealing how bilingual school curricula involving a language switch might affect cognitive processes until adulthood. More generally, this study supports the importance of language in numerical cognition.

Constraints on Generality

We expect the result to generalize to high and low proficient bilinguals of other languages given a sequential acquisition of the languages and a strict control of the stimuli. For example, both languages must have comparable lengths (or otherwise see N. C. Ellis & Hennelly, 1980). Given that the stimuli used here are slightly longer in German than in French (see Table 2 in the online supplemental materials), but the response times were shorter for the former, these should generalize to other stimuli. Note, however, that multidigit numbers might present additional morpho-syntactic language differences which might explain additional costs or benefits when comparing languages (see Lachelin et al., 2022). Hence, we have no reason to believe that the results depend on other characteristics of the participants, materials, or context.

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