Running header: How bilingualism affects two-digit number transcoding?

Title: Units first or tens first: How bilingualism affects two-digit number transcoding?*

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Abstract

We investigated the influence of language on transcoding in bilinguals and monolinguals.

Bilingual adults who learned math in German (LM+) during primary school and in French during secondary school (LM-) were compared to German and French monolinguals. Participants had to listen to two-digit numbers and had to identify the heard number amongst four visually presented Arabic numbers. To mimic the German vs. the French number word systems, the order of visual appearance of the units and tens of the two-digit numbers was manipulated. Participants also performed a classical transcoding task with simultaneous appearance of the tens and units. Bilinguals were faster to transcode in LM+ than in LM-. Furthermore, they were slower and made more errors when transcoding in LM- compared to monolingual French-speaking participants. We conclude that math acquisition's language influences simple numerical tasks such as transcoding in adulthood, confirming the critical role of language in numerical cognition.

Keywords: Transcoding, bilingual, monolingual, inverted two-digit numbers structure.

1. Theoretical Background

Everybody can manipulate quantities without the need of the language (e.g. Gelman & Butterworth, 2005). For example, newborns (Xu, Spelke, & Goddard, 2005) but also chicks (Rugani, Regolin, & Vallortigara, 2008) and frogs can discriminate large number of items in an approximate manner. Nevertheless, the exact representation of large numerical quantities require to be learned through language (Lemer, Dehaene, Spelke, & Cohen, 2003; Pica, Lemer, Izard, & Dehaene, 2004).

According to the triple code model (Dehaene, 1992), three different codes are used to represent numbers. The analogic code which is related to quantity (e.g. the number of trouts under the bridge), the verbal code corresponding to verbal numbers (e.g. “forty-two”, “twenty-eight”), and the visual code corresponding to visual Arabic digits (e.g. 42, 28). Each of the three codes uses different cerebral substrates and they are linked together by three routes. The action of moving from one code to another is called transcoding. For example, reading the Arabic digit 42 implies transcoding from the visual (i.e. 42) to the verbal form (i.e. “forty-two”).

Specific languages and their associated verbal number forms are known to facilitate or to impede the acquisition of mathematics. Asian children have for instance an earlier mastery of the place value concept than their western peers (Miura et al., 1994). This effect is attributed amongst others to the fact that Asian languages are more transparent than western languages. Transparency refers to the degree to which the number words in a language follow the Arabic notation. For example, 92 in Japanese 92 is pronounced as “kyūjū ni” (nine ten two) while in French it is pronounced as “quatre-vingt-douze” (four twenty and twelve). In German and Dutch there is an inversion between tens and units in the verbal compared to the visual form; 92 is respectively pronounced as “Zweiundneunzig” in German and “tweënnegentig” in Dutch (two

and ninety). Several studies showed that this inversion property could impede number and mathematic acquisition. For instance, Poncin, Van Rinsveld, & Schiltz, (submitted for publication) reported that French-speaking children were faster to transcode two-digit numbers than German-speaking children. Helmreich & al., (2011) showed that Italian-speaking children were better than German-speaking children at placing two-digit numbers on a corresponding physical line. Göbel, Moeller, Pixner, Kaufmann, & Nuerk, (2014) reported that German-speaking children had a higher carry effect when they performed addition than their Italian peers at the same age. According to Lonnemann & Yan, (2015) the inversion structure of the German number-words still causes difficulties to mature and educated adults. They showed that German-speaking adults had more difficulties than Chinese-speaking participants to perform additions with reports. Evidence from brain-damaged patients revealed that German-speaking adults with left parietal lesions had difficulties to write (Sittig, 1921) and to read aloud (Blanken, Dorn, & Sinn, 1997) two-digit numbers without making inversion errors (e.g. write 24 instead of 42). Another lesion study showed that a Greek – German bilingual patient was not able to write two-digit numbers in German without making inversion errors while writing in Greek was not a problem (Proios, Weniger, & Willmes, 2002).

Knowing that the structure of number words matters in numerical cognition, bilinguals' performances at numerical tasks are highly relevant to examine. This is especially true nowadays because of the increasing complexification of children's language profiles, as bilingual or multilingual learners start to outnumber monolinguals in many schools (Grosjean, 2010). The literature often distinguishes balanced from unbalanced bilinguals. While the former are able to speak two languages with the same proficiency, the latter also master two languages but have a systematic preference and advantage for one of those (Guijarro-Fuentes, Larranaga, & Clibbens,

2008; Müller & Pillunat, 2008). Unbalanced language proficiency levels are often coupled with distinct moments of language acquisition during life, leading to a first learned language L1 usually mastered better than a later learned second language (L2). In particular, another critical notion for numerical cognition is the language of math acquisition. Several studies highlighted the role of the language of math acquisition in mathematical abilities and especially arithmetic. Below we will briefly describe the influence of bilingualism on arithmetic problem solving and number comparison, before introducing the present study investigating transcoding in bilinguals.

Data on balanced bilinguals show for example that 14 to 19 years-old teenagers were slower and made more mistakes than their monolingual peers in complex arithmetical problems including more than two operations (Mägiste, 1980). Similarly, Geary, Cormier, Goggin, Estrada, & Lunn, (1993) showed that balanced adult bilinguals were slower than unbalanced bilinguals when computing carry operations. According to both aforementioned studies, these results could be due to the fact that balanced bilinguals had difficulties to disregard one of their languages during complex computations.

Studies on unbalanced bilinguals indicate that they might use translation processes converting arithmetical operations into their preferred language before solving it. For example, an fMRI study by Wang, Lin, Kuhl, & Hirsch, (2007) highlighted an additional recruitment of language-related processes when unbalanced Chinese-English bilinguals were confronted with arithmetical problems in their second language, while this was not the case in their first language. The authors concluded that bilinguals translate arithmetic problems from their L2 to their L1. Another study led to the same conclusions because the unbalanced Chinese-English bilinguals participants had higher activation in the left frontal areas when they performed mental additions using their L2 (Lin, Imada, & Kuhl, 2012). In contrast, a more recent fMRI study (Van

Rinsveld, Dricot, Guillaume, Rossion, & Schiltz, 2017) did not find any support for the existence of translation mechanisms in a population of much more balanced bilinguals. It rather pointed towards the activation of partly different neuronal substrates when calculating in different languages without evidence of translations processes. Further evidence for a crucial role of the language of math acquisition comes from a study from Bernardo (2001), in which Filipino-English bilingual high school students had to verify the correctness of arithmetical problems. This study showed that it was easier for participants to respond in LM+, even though the latter was not their dominant language. Salillas & Wicha, (2012) showed that participants' brain potentials resulting from the presentation of simple multiplications (i.e. multiplication tables) in LM+ were similar to brain potentials obtained from simple digit presentation, while the presentation of simple multiplication in LM- led to qualitatively different brain potentials. This finding was also true when LM+ was not the dominant language. Finally, Saalbach, Eckstein, Andri, Hobi, & Grabner, (2013) showed that after a training session of arithmetical problems in French or in German, high school students who participated in a bilingual French-German education program had a higher cognitive cost when the trained arithmetical problem was asked in the language that had been not used during training. All these studies suggest that language of math acquisition significantly impacts bilingual's arithmetic skills.

Performance in more basic numerical tasks than arithmetic, as for instance symbolic number comparisons, is also impacted by bilingualism. In 2001, Nuerk, Weger, & Willmes, described the existence of compatibility effects during two-digit number comparison, corresponding to faster responses and lower error rates for compatible trials in which both tens and units of the two compared numbers lead to the same decision (e.g.: $42 < 87$, $4 < 8$ and $2 < 7$) than incompatible comparison trials in which tens and units lead to different decisions (e.g. : 28

< 42 , $2 < 4$ but $8 > 2$). In monolinguals, this compatibility effect is well-known to be influenced by the number word structure. Languages using unit-ten number word structures such as German led to classical compatibility effects (Nuerk, Weger, & Willmes, 2002), while languages using ten-unit structure such as English or Italian led to inverted compatibility effects (Macizo & Herrera, 2010; Nuerk, Weger, & Willmes, 2005). Similar effects have been shown in bilinguals, such that, the direction of the compatibility effect was depending on the language in which the task was performed. A regular compatibility effect occurred when the used language had a unit-ten structure and an inverted compatibility effect was observed when the used language had a ten-unit structure (Macizo, Herrera, Paolieri, & Román, 2010; Macizo, Herrera, Román, & Martín, 2011).

To the best of our knowledge, the influence of bilingualism on number transcoding, an even more basic task, has never been investigated in bilingual adults so far. In a previous cross-linguistic comparison, we examined the influence of language on transcoding in adults (and children) by comparing transcoding performances of two language groups with different number word structures. This comparison of German- and French-speaking monolinguals revealed no transcoding performance differences between adults of both language groups (Poncin, Van Rinsveld, & Schiltz, submitted for publication). This can be expected given the very high skill levels that are reached by numerate adults in this task. Nevertheless, it remains to be tested whether and how mastery of two languages by the same person impacts transcoding. Questions to be addressed are: (a) Do bilinguals transcode numbers similarly in their two languages? (b) Do bilinguals transcode numbers in each of their languages in a similar manner than their monolingual peers?

In the present study, we assessed transcoding performances of German-French bilingual adults, as well as their monolingual German- and French-speaking peers. As in Poncin, Van Rinsveld, & Schiltz, (submitted for publication), we used a transcoding paradigm in which participants had to listen to two-digit numbers and match them with a visually presented target stimulus presented among three distractors. Manipulating the order of appearance of tens and units led to three conditions: (1) The “tens-first” condition in which the tens of the target and the three distractors appeared before the units. This condition mimics the French number-word structure, with tens being pronounced before units (e.g. “vingt-trois” corresponding to “twenty-three”). (2) The “units-first” condition, in which the units of the target and the three distractors appeared before the tens. This condition mimics the German number-word system, with units being pronounced before tens (e.g. “Dreiundzwanzig” corresponding to “twenty-and-three”). (3) The “simultaneous” condition in which tens and units appeared at the same time. This condition is the more natural and ecological one, as in everyday life we are typically confronted with two-digit numbers in this format.

Concerning performances in bilingual participants, we hypothesized that performances should overall be better in German than French, since the former is their language of math acquisition. This advantage should be especially visible in the “units-first” condition, because it additionally mimics the German pronunciation of two-digit numbers. In contrast the fact that French pronunciation of two-digit numbers is imitated in the “tens-first” condition should facilitate bilinguals’ performance in French, yielding less pronounced or no language differences in this condition. In contrast, we again expected a clear advantage for German in the “simultaneous” condition due to the fact that math was learned in German by the present bilinguals.

When comparing bilingual and monolingual French-speaking participants, we hypothesized that monolinguals should be faster in all or most conditions, because French is their language of math acquisition, while this is not the case for the bilingual participants. Comparing bilingual and monolingual German-speaking participants, both groups should have similar performances in the three conditions given the fact that both acquired math in German. Nevertheless a possibly higher flexibility due to a potential bilingualism advantage in executive functions might advantage bilinguals performance in the sequential conditions (e.g. Adesope, Lavin, Thompson, & Ungerleider, 2010).

2. Methods

2.1. Bilingual Participants

Twenty-nine Luxemburgish bilingual German– and French-speaking adults (17 females $M_{\text{age}} = 24.18$; $SD_{\text{age}} = 6.1$) were recruited by email among the student population of the university of Luxembourg. All participants had Luxemburgish as mother tongue (official language of Luxembourg which is a dialectal variant of German) and were schooled through the Luxemburgish school system. Thus, all participants had attended primary school (composed of 6 grades) with German as instruction language. French was learned as a second language (mean age of starting to learn French: 7.5 years, $SD = 1.2$) from the second year of primary school onward. In secondary school (composed of 7 grades) French then became the predominant instruction language. When reaching the highest grades of secondary school participants were thus bilinguals with high proficiency levels in both German and French, corresponding to a level of proficiency equivalent to C1 in terms of European Framework of Reference¹. With respect to numeracy, basic mathematics was acquired exclusively in German during primary school, while more complex mathematics was learned in French from secondary school onwards. Therefore, we consider German as the first and French as the second language of instruction. Moreover, participants were German-French bilinguals with similar trajectories not only of language acquisition but also of language of instruction for mathematic.

2.2. Monolingual Participants

Twenty-eight French-speaking adults (17 female, Mean age (M_{age}) = 22.36, Standard Deviation age (SD_{age}) = 4.4 and twenty-six German-speaking adults (10 female, M_{age} = 26.35 SD_{age} = 3.71) were recruited by email among the student population of the universities of Luxembourg and Berlin. We only selected French- or German-speaking participants who learned mathematics in French or German, respectively. Written consent was obtained before the study and the local Ethics Review Panel approved the study. Monolingual participants were the same than in Poncin et al., (n.d.).

2.3. Ethical concerns

Written consent was obtained before the study and the local Ethics Review Panel approved the study. Participants were rewarded by a monetary recompense.

2.4. Materials and Procedures

Transcoding tasks

The transcoding task was presented on an Apple 13' Macbook using Psyscope X B57 (Cohen, Mac Whinney, Flatt, & Provost, 1993). Response times were recorded with the Iolab USB Button Box. It consisted in listening to a spoken number word presented via headsets (over both ears) and finding the matching Arabic number amongst four numbers presented on a computer screen (see Figure 1). Critically, we constructed three conditions in which we systematically manipulated the timing at which unit- and ten-digits appeared on the screen. In the two sequential presentation conditions ten-digits appeared 500ms before the unit-digits in the “tens-first” condition and unit-digits appeared 500ms before the ten-digits in the “units-first”

condition. In the ecological “simultaneous” condition tens and units appeared simultaneously. All three conditions contained the 42 target stimuli and their corresponding three distractors in random order. The order of the three conditions was counterbalanced across participants. Each condition was preceded by 12 warmup items with feedback.

The four vertical locations of the numbers on the screen were spatially arranged in the same manner as the response buttons on the button box and numbers had the same color background as the corresponding buttons on the Iolab USB Button Box (see Figure 1). Response times corresponded to the period between the onset of the last digit (i.e. ten-digit or unit-digit for the “units-first” and the “tens-first” conditions, respectively) and the onset of participants’ response. Please note that response-times of sequential and “simultaneous” conditions cannot be compared directly due to differences in information content at the start of the response recording period. While participants need to process the two digits in the “simultaneous” condition, one of the digits (i.e. ten-digit in the “tens-first”; unit-digit in the “units-first”) has already been processed in the sequential conditions.

The 42 target-stimuli consisted of all numbers between 23 and 87, except ties (e.g. 22) and tens (e.g. 20). As distractor-stimuli we used: (1) “unit distractors” in which one unit was randomly added or subtracted to the heard number (e.g. for 42 distractor was 43 or 41), (2) “ten distractors” in which ten units were randomly added or subtracted to the heard number (e.g. for 42 the distractor was 32 or 52), (3) “inversion distractors” where units and tens were inverted (e.g. for 42 the distractor was 24). To avoid bias in our distractor stimuli (i.e. impossibility to create “unit distractors” and “ten distractors” with 1 or 9 while respecting the above-mentioned principles), we also removed numbers containing 1 or 9 (e.g. 31; 92; 49) Stimuli were recorded by native German- and French-speakers. Position of the target was randomly assigned among the

four possible positions on the screen and the same location was not repeated more than two times. Targets appeared at least ten times in each of the four positions.

<Insert Figure 1 about here>

Reasoning test

In order to control for reasoning skills across linguistic groups, we assessed participants with the subtest of categories from the Snijders Oomen non-verbal intelligence test SON-R-6-40 (Tellegen, P. J., Laros, J. A., & Petermann, 2012). The subtest of Categories consisted in identifying the common properties of three pictures and determining the two pictures among five novel alternatives, which possess the same properties.

Participants were tested individually in a quiet room. We first administrated the reasoning test and then participants underwent the experimental transcoding tasks. During the experimental tasks, participants sat in front of the screen with their eyes approximately 60 cm of the screen. The present tests lasted about 45 min and were part of a larger data collection.

3. Results

In order to investigate the results of the three transcoding tasks, we analyzed the sequential conditions (i.e. “tens-first” and “units-first”) and the ecological transcoding condition (i.e. “simultaneous”) separately. In the sequential conditions, participants could indeed eliminate two distractors before the complete appearance of the stimuli. More precisely, during the “tens-first” condition participants could directly eliminate the inversion-distractor and the tens-distractor as soon as the unit was presented and then make a choice among the two remaining alternatives. Similarly, the inversion-distractor and the unit-distractor could be eliminated in a first step during the “units-first” condition. In contrast, during the “simultaneous” condition, participants were immediately confronted to the appearance of whole two-digit numbers and had

to make their choice among four different stimuli. All statistical analyses were performed using JASP software (JASP Team, 2018).

To assure that groups were comparable in terms of general cognitive abilities, participants' general reasoning abilities were assessed and compared. Before analysing transcoding performances, the mean scores and standard deviations of the *reasoning test* were computed and all participants scoring higher or lower than 2.5 standard deviations from the group mean were removed. This led to the removal of two German-speaking participants scoring lower than their peers (29.57 ± 3.4). When comparing the reasoning scores of the two monolingual groups and the bilingual groups, no significant differences were observed ($M_{GE} = 29.57$, $SD_{GE} = 3.4$; $M_{FR} = 27.33$, $SD_{FR} = 4.64$, $M_{BI} = 26.64$, $SD_{BI} = 4.74$; $F(2;75) = 3.03$, $p > .05$).

Considering performance in the *transcoding tasks*, all participants with an error rate exceeding 2.5 standard deviations from the group mean were excluded from the dataset prior to the analyses. By applying this procedure, we removed one participant from the French-speaking group, one from the German group and one from the bilingual group. We also removed all response times that were not comprised in the interval of ± 2.5 standard deviations from the mean of each participant and which exceeded 5000ms ($M_{FR} = 874\text{ms}$, $SD_{FR} = 130\text{ms}$; $M_{GE} = 925\text{ms}$, $SD_{GE} = 227\text{ms}$, $M_{BI} = 932\text{ms}$, $SD_{BI} = 183\text{ms}$). Following this procedure 3.67% and 4.8% of trials were removed in the French-speaking and German-speaking monolingual participants, respectively. In bilingual participants, 3.46% and 2.75% were removed in the French and German task respectively. Response time analyses were computed only on correctly responded trials.

3.1. Error rate analyses

Performance within bilingual group

In order to compare the percentage of error rates of the two sequential transcoding conditions between languages, we performed a 2x2 ANOVA for repeated measure with the condition (“tens-first” & “units-first”) and language (French & German) as within-group factors (see table 1 for descriptive statistics). Main effect of condition, and main effect of language were not significant (Condition effect: $F(1, 27) = .064, p = .802, \eta^2 = .002$; Language effect: $F(1, 27) = .576, p = .455, \eta^2 = .021$;). In addition, we observed a non-significant interaction between language and condition ($F(1, 27) = .006, p = .937, \eta^2 < .001$).

<Insert Table 1 about here>

Follow-up two-sided paired t-test Bonferroni corrected for multiple comparisons were performed on the percentage of error rates of the “tens-first” and “units-first” conditions. We did not observe any significant differences between French and German task performance in bilingual participants (“tens-first”: $t(27) = .491, p = 1, d = .093$; “units-first”: $t(27) = .673, p = 1, d = .127$; “simultaneous”: $t(27) = 1.655, p = .218, d = .313$).

French bilingual vs. French monolingual performance

In order to compare the percentage of error rates of the French bilingual participants with the monolingual French-speaking participants, we performed a 2x2 ANOVA for repeated measures with the sequential conditions (“tens-first” & “units-first”) as within-groups factor and

the language profile (monolingual French vs. bilingual French) as between-group factors. Only the main effect of language profile was significant (Language profile effect: $F(1,53) = 5.3, p = .025, \eta^2 = .091$). However, the main effect of condition ($F(1, 53) = .298, p = .587, \eta^2 = .006$) and the interaction between language-profile and condition ($F(1,53) = .519, p = .474, \eta^2 = .01$) were not significant.

Follow-up two-sided paired t-test Bonferroni corrected for multiple comparisons were performed on the percentage of error rates of the “tens-first” and “units-first” conditions. We observed a significant difference of error percentage between monolingual French-speakers and French task performance of bilingual participants in the “tens-first” and “simultaneous” conditions (“tens-first”: $t(53) = 2.682, p = .020, d = .723$; “units-first”: $t(53) = 1.222, p = .454, d = .330$; “simultaneous”: $t(53) = 2.789, p = .014, d = .752$).

German bilingual vs. German monolingual performance

In order to compare percentage of error rates of the bilingual participants with the monolingual German-speaking participants in the two sequential conditions, we performed a 2x2 ANOVA for repeated measure with the conditions (“tens-first” & “units-first”) as within-groups factor and the language profile (monolingual German vs. bilingual German) as between-group factors. Main effects of condition and language profile were not significant (Condition effect: $F(1,49) = .03, p = .862, \eta^2 = .004$; language-profile effect: $F(1, 53) = .664, p = .419, \eta^2 = .013$). Moreover, the interaction between language-profile and condition was not significant ($F(1,49) = .03, p = .862, \eta^2 = .004$).

Follow-up two-sided paired t-test Bonferroni corrected for multiple comparisons were performed on the percentage of error rates of the “tens-first” and “units-first” conditions. We did not observe any significant differences between French and German task performance in

bilingual participants (“tens-first”: $t(49) = .828, p = .824, d = .233$; “units-first”: $t(49) = .548, p = 1, d = .154$; “simultaneous”: $t(49) = -.458, p = 1, d = -.129$).

Within language comparison of the sequential conditions

In order to investigate differences between the sequential conditions, we performed paired two-sided t-test between “tens-first” and “units-first” condition in each language group. T-tests between “tens-first” and “units-first” conditions in the French and German task versions of bilinguals were not significant (French-speaking bilinguals: $t(27) = .109, p = .914, d = .021$; German-speaking bilinguals: $t(27) = .25, p = .805, d = .047$). Neither were there any significant differences between these conditions in monolingual participants (French-speaking monolinguals: $t(26) = -1.07, p = .294, d = -.206$; German-speaking monolinguals: $t(22) = 0, p = 1, d = 0$).

In sum, error analyses revealed that bilinguals were less accurate in French than their monolingual French-speaking peers. Errors concerned specifically the “tens-first” and the “simultaneous” conditions.

3.2. Response time analyses within bilingual group

Between languages comparisons of the sequential conditions

In order to compare the performances in the two sequential transcoding conditions between languages, we performed a 2x2 ANOVA for repeated measure with the condition (“tens-first” & “units-first”) and language (French & German) as within-group factors. Both the main effect of condition and language were significant (Condition effect: $F(1, 27) = 108.46, p < .001, \eta^2 = .801$; Language effect: $F(1, 27) = 16.37, p < .001, \eta^2 = .377$). In addition, we

observed a significant interaction between language and condition ($F(1, 27) = 26.95, p < .001, \eta^2 = .5$).

Follow-up two-sided paired t-test Bonferroni corrected for multiple comparisons were performed on “tens-first” and “units-first” conditions. According to our hypothesis, the “tens-first” condition should favour participants’ performance in French, given that it emulates the French number word structure. However, two-sided t-tests indicated that performances did not significantly differ between bilinguals’ languages in the “tens-first” condition ($t(27) = 1.64, p = .224, d = .31$ with $M_{FR} = 778\text{ms}$, $SD_{FR} = 236$, $M_{GE} = 722\text{ms}$, $SD_{GE} = 171$). In the “units-first” condition which emulated the German structure of number words we expected bilingual participants to be faster in German, which is in addition their language of math acquisition. A two-sided paired t-test Bonferroni corrected for multiple comparisons indicated that performance in the «units-first» conditions differed indeed significantly between French and German in favour of German ($t(27) = 6.34, p < .001, d = 1.2$ with $M_{FR} = 1013\text{ms}$, $SD_{FR} = 224$, $M_{GE} = 835\text{ms}$, $SD_{GE} = 191$).

Between languages comparisons of the simultaneous condition

The influence of language on performances in the “simultaneous” transcoding condition was analysed with two-sided paired t-tests. In line with our hypothesis that bilingual participants should be faster in their language of math acquisition (i.e. German), performance in French and German significantly differed for the “simultaneous” condition in favour of German ($t(27) = 4.08, p < .001, d = .77$, with $M_{FR} = 1042\text{ms}$, $SD_{FR} = 274\text{ms}$, $M_{GE} = 905\text{ms}$, $SD_{GE} = 152\text{ms}$) (see left part of Figure 2a).

Within languages comparisons

To investigate the effect of condition (“tens-first” vs. “units-first”) in the sequential presentation mode, mean response times per condition and participants were compared in a paired two-sided t-test that was computed for the French and the German tasks, respectively. We observed a significant difference of condition in French ($t(27) = -9.469, p < .001, d = 1.789, M_{\text{TensFirst}} = 778\text{ms}, SD_{\text{TensFirst}} = 236; M_{\text{UnitsFirst}} = 1013\text{ms}, SD_{\text{UnitsFirst}} = 224$) and in German ($t(27) = -7.652, p < .001, d = 1.446, M_{\text{TensFirst}} = 722\text{ms}, SD_{\text{TensFirst}} = 171; M_{\text{UnitsFirst}} = 835\text{ms}, SD_{\text{UnitFirst}} = 191$), such that the “tens-first” condition was always performed faster.

In sum, analyses revealed that bilinguals were faster in German (i.e. their language of math acquisition) than in French during the “units-first” condition and they were equally fast in both languages during the “tens-first” condition. Like in the “units-first” condition responses were also faster in German during the ecological “simultaneous” condition. In both of bilinguals’ languages, transcoding was completed faster during the “tens-first” than during the “units-first” condition.

3.3. French bilingual vs. French monolingual performance

Between languages comparisons of the sequential conditions.

In order to compare the French performances of the bilingual participants with the monolingual French-speaking participants, we performed a 2x2 ANOVA for repeated measures with the sequential conditions (“tens-first” & “units-first”) as within-groups factor and the language profile (monolingual French vs. bilingual French) as between-group factors. Only the main effect of condition was significant (Condition effect: $F(1,53) = 148.111, p < .001, \eta^2 = .718$; Language-profile effect: $F(1, 53) = 1.983, p = .165, \eta^2 = .036$). In addition, we observed

a significant interaction between language-profile and condition ($F(1,53) = 5.084, p = .028, \eta^2 = .025$).

Follow-up two-sided independent t-tests Bonferroni corrected for multiple comparisons were not significant between language profiles in both sequential conditions (units-first : $t(53) = 2.02, p = .096, d = .545$ with $M_{BI} = 1013\text{ms}, SD_{BI} = 224, M_{FR} = 906\text{ms}, SD_{FR} = 161$; tens-first: $t(53) = .64, p = 1, d = .174$ with $M_{BI} = 778\text{ms}, SD_{BI} = 236, M_{FR} = 745\text{ms}, SD_{FR} = 131$) (see right part of Figure 2b).

Between languages comparisons of the simultaneous condition

A two-sided independent t-test indicated a significant difference between language profiles in favour of the monolingual French-speaking group ($t(53) = 2.351, p = .022, d = .634$, with $M_{BI} = 1042\text{ms}, SD_{BI} = 274, M_{FR} = 907\text{ms}, SD_{FR} = 122$) (see left part of Figure 2b).

Within language comparisons

To investigate the effect of condition (“ten-first” vs. “units-first”) in the sequential presentation mode in French monolingual speakers, mean response times per condition and participants were compared in a paired two-sided t-test. We observed a significant difference between conditions ($t(26) = 7.715, p < .001, d = 1.485$ $M_{\text{TensFirst}} = 745\text{ms}, SD_{\text{TensFirst}} = 131$; $M_{\text{UnitsFirst}} = 906\text{ms}, SD_{\text{UnitsFirst}} = 161$), such that the «tens-first» condition led to faster responses. For results concerning these analyses of bilinguals French performances please see section 3.2.3 Performances within bilingual group/within language comparisons.

In sum, analyses revealed that in both sequential conditions bilinguals were as fast as in French as monolingual French-speakers . Nevertheless, monolingual French-speakers outperformed bilinguals in the ecological “simultaneous” condition. Presenting two-digit numbers

in a decomposed sequential manner starting with tens (i.e. “tens-first”) facilitated transcoding compared to the “units-first” presentation in both language groups.

3.4. German bilingual vs. German monolingual performance

Between languages comparisons of the sequential conditions

In order to compare performances of the bilingual participants with the monolingual German-speaking participants in the two sequential conditions, we performed a 2x2 ANOVA for repeated measure with the conditions (“tens-first” & “units-first”) as within-groups factor and the language profile (monolingual German vs. bilingual German) as between-group factors. Main effects of condition and language profile were significant (Condition effect: $F(1,49) = 112.253$, $p < .001$, $\eta^2 = .694$; language-profile effect: $F(1, 53) = 4.44$, $p = .04$, $\eta^2 = .083$). However, the interaction between language-profile and condition was not significant ($F(1,49) = .472$, $p = .495$, $\eta^2 = .003$).

Two-sided independent follow-up t-tests Bonferroni corrected for multiple comparisons indicated that performance did not depend on language profile in the “units-first” condition, nor in the “tens-first” condition (“tens-first”: $t(49) = -1.969$, $p = .11$, $d = -.554$ with $M_{BI} = 722\text{ms}$, $SD_{BI} = 171$, $M_{GE} = 853\text{ms}$, $SD_{GE} = 295$; “units-first”: $t(49) = -2.182$, $p = .068$, $d = -.614$ with $M_{BI} = 835\text{ms}$, $SD_{BI} = 191$, $M_{GE} = 981\text{ms}$, $SD_{GE} = 285$)(see right part of Figure 2c).

Between languages comparisons of the simultaneous condition

A two-sided independent t-test also failed to find a difference related to language-profile in the ecological “simultaneous” condition (Simultaneous: $t(49) = .803$, $p = .426$, $d = .226$, with $M_{BI} = 905\text{ms}$, $SD_{BI} = 152$, $M_{GE} = 873\text{ms}$, $SD_{FR} = 127$)(see left part of Figure 2c).

Within language comparisons

To investigate the effect of condition (“tens-first” vs. “units-first”) in the sequential presentation mode in German monolingual speakers, mean response times per condition and participants were compared in a paired two-sided t-test. We observed a significant difference of condition ($t(22) = 7.303, p < .001, d = 1.523$ $M_{\text{TensFirst}} = 853\text{ms}$, $SD_{\text{TensFirst}} = 295$; $M_{\text{UnitsFirst}} = 981\text{ms}$, $SD_{\text{UnitsFirst}} = 285$), such that the “tens-first” condition led to faster responses. For results concerning these analyses of bilinguals German performances please see section 3.2.3.

Performances within bilingual group/within language comparisons.

In sum, analyses revealed an effect of language profile in favour of bilinguals in sequential conditions. Moreover we did not find any evidence for performance differences between language profiles in the “simultaneous” condition, in line with the fact that German was the language of mathematic acquisition in both groups, as further discussed below. Furthermore, presenting two-digit numbers in a decomposed sequential manner starting with the tens (i.e. “tens-first”) facilitated transcoding compared to the “units-first” presentation in both language groups.

<Insert Figure 2 about here>

4. Discussion

The present study aimed to assess the influence of language and more specifically bilingualism on two-digit number transcoding. To this aim, we recruited German- French bilinguals, to compare their performances to both groups of French- and German-speaking monolinguals. Bilingual participants acquired mathematics in German (LM+) in primary school (lasting 6 years) and switched to French for mathematics learning (LM-) in secondary school (lasting 7 years). The transcoding task consisted in matching a heard two-digit number with its visually presented pair displayed amongst three distractors. Critically, we manipulated the order of appearance of tens and units, which led to the creation of two sequential conditions. In the “tens-first” condition, the French number-word system was visually emulated by presenting tens 500ms before the units. In the “units-first” condition, the German number-word system was imitated by presenting the units 500ms before the tens. In a third, more ecological condition termed “simultaneous” tens and units appeared at the same time.

In line with our hypothesis that transcoding is more efficient in the language of math acquisition, **bilinguals** responded faster in German, i.e. their LM+ compared to French, i.e. their LM- in the “units-first” and “simultaneous” conditions. Moreover they performed the “tens-first” condition similarly fast in both of their languages. Concerning error rates there were no differences when comparing bilinguals’ conditions amongst each other. We suggest that bilinguals’ shorter response times in LM+ in the ecological “simultaneous” condition could be due to the fact that associations between verbal and visual forms of number-words are stored in the verbal format of LM+ in long-term memory (see Barrouillet (2018), for a discussion about the specific role of long-term memory in numbers and facts retrieval). In contrast, when the participants had to perform the task in their LM-, they could not directly associate the

corresponding number word with the corresponding Arabic number form but needed to rely on more complex alternative processing, leading to additional cognitive processing reflected in longer response times. Bilinguals are indeed known to store arithmetical facts in long-term memory in the verbal format of the language in which they were learnt and these facts are not transferable to another language (Campbell & Epp, 2004; HAHN, SAALBACH, & GRABNER, 2017; Saalbach et al., 2013; Spelke & Tsivkin, 2001; Venkatraman, Siong, Chee, & Ansari, 2006; Volmer, Grabner, & Saalbach, 2018). Relatedly, bilinguals are faster and more accurate to perform verification of correctness tasks in their LM+ than LM-, even if LM- is their mother tongue (Bernardo, 2001). This advantage in LM+ compared to mother tongue was also found for simple multiplication in adult population (Salillas & Wicha, 2012). In a study with a similar population of bilingual participants (Van Rinsveld, Brunner, Landerl, Schiltz, & Ugen, 2015), we recently observed that not only complex (solutions up to 99) but even simple addition problems with one-digit addends were solved slower in LM- (i.e. French) than in LM+ (i.e. German). If we assume that Arabic numerical forms are associated with the corresponding number-words in LM+, the ADAPT (A Developmental, Asemantic and Procedural Transcoding model) model proposed by Barrouillet and colleagues (Barrouillet, Camos, Perruchet, & Seron, 2004) could explain our results. This asemantic model describes transcoding processes as an algorithmic strategy of direct retrieval of Arabic numerical forms in long-term memory. More precisely, according to ADAPT, verbal inputs are thought to be stored in a phonological buffer and are transcoded into Arabic numbers by a parsing procedure and a production system which compares each element of the verbal string with the corresponding association between verbal number forms and Arabic number forms in long-term memory. Nevertheless, along development and with increasing transcoding mastery, correspondence between verbal and Arabic formats of two-

digit numbers are supposed to be stored in long-term memory (LTM) and directly retrieved, without using the production system. Considering that knowledge stored in LTM in a given language is not transferable to another language (Marian & Fausey, 2006; Volmer et al., 2018), two-digit numbers would therefore be associated with their corresponding verbal forms in LM+. When transcoding in LM-, bilinguals could not rely on the associations stored in long term memory and would be slowed by the use of more complex processing such as using the production system or using translation in LM+ strategy.

Comparing bilinguals with **French**-speaking monolinguals, showed that bilinguals were slower in French transcoding than their monolingual peers in the “units-first” condition. While no response time differences between language groups were observed in the “tens-first” condition, the latter nevertheless yielded more errors in bilinguals. Thus both decomposed conditions led to poorer performances in the bilingual group, probably because French was monolingual French-speakers LM+, while this was not the case for bilinguals. In line with this interpretation bilinguals were significantly slower and more error-prone in the “simultaneous” condition. The increased error rates could also indicate translation from LM- to LM+ and back. The fact that French and German are inverted regarding their tens-units structure might indeed lead to translation errors, thus making transcoding in LM- more error-prone.

Comparing transcoding performances of bilinguals and monolingual **German**-speakers pointed towards differences favoring bilinguals in the sequential conditions. Those results could be explained by better executive abilities. Fluently speaking two or more languages could indeed enhance executive functions and contribute this way to better numerical performances (Adesope et al., 2010; Bialystok, 2009; Hartanto, Yang, & Yang, 2018; Stocco & Prat, 2014). For example, Prior, Katz, Mahajna, & Rubinsten (2015) showed that bilinguals speaking a language with tens-

units and a language with units-tens number-word structures had better flexibility abilities, which in turn would give them an advantage in arithmetic compared to monolinguals. Those data suggested a link between bilingualism, an enhanced executive system and better arithmetical performances, though the existence of such links are still debated in the literature. The first link (i.e. bilingualism – executive functions) has been criticized regarding their statistical validity (i.e. poor statistical power due to small amount of participants, dubious statistical analysis or high risk of type-one statistical errors, lack of reproducibility) or the control of confounding variable such as socioeconomic status or cultural differences (de Bruin, Treccani, & Della Sala, 2015; Morton & Harper, 2007; Paap, 2014, 2016; Paap et al., 2017; Paap, Johnson, & Sawi, 2015, 2016; Paap & Greenberg, 2013; von Bastian, Souza, & Gade, 2016). Moreover a meta-analysis demonstrated a publication bias exclusively supporting the emergence of studies showing such relation between bilingualism and better executive abilities (de Bruin et al., 2015). In addition the relation between executive system and arithmetic has been controversially discussed in a recent literature review (Archambeau & Gevers, 2018) which recommends caution to consider this relation as real, because there is not enough empirical evidence supporting it. To our knowledge the relation between executive system and transcoding has not been studied yet. The present results also need to be interpreted with caution since only the main effect of condition was significant, but independent t-tests failed to highlight significant difference between languages.

Concerning the “units-first” condition, it is possible that emulation of the unit-ten structure of German number-words did not help German-speakers to transcode faster. Rather, this condition seems to be more difficult in both German and French. One potential explanation is its incongruence regarding the western left-to-right reading direction of two-digit Arabic

numbers. Consequently, the “units-first” condition could require more cognitive load and be easier when it is performed in LM+. Accordingly, the fact that the “tens-first” condition was performed significantly faster than the “units-first” condition both in German and French suggests that revealing the tens before the units generally corresponds to a helpful clue for transcoding. This might reflect the fact that adults in western cultures read from left to right and consequently the “tens-first” sequential condition is closer to typical reading situations than the “units-first” condition. These results might also be due to the place-value coding system and the fact that ten digits positioned on the left side convey a ten-fold higher quantity than the right-sided unit digits and therefore receive more processing weight. In any case, the behavioral pattern do not support the proposal that two-digit numbers are represented holistically on a unique mental number line without distinguishing the respective contributions of tens and units (Dehaene, Dupoux, & Mehler, 1990), but rather back-up the view that two-digit numbers are represented in a decomposed manner (Nuerk, Kaufmann, Zoppoth, & Willmes, 2004). However, when interpreting the present data, one needs to consider that the visual presentation format in the decomposed conditions is relatively unusual and might have led participants to adopt special strategies in this specific situation.

Finally, in the “simultaneous” condition we did not find any response speed or error differences between bilinguals and monolingual German-speakers. As the two groups had German as language of math acquisition, this confirmed the expected importance of the LM+ in transcoding.

To the best of our knowledge, these results are the first to indicate an influence of the language of math learning on transcoding abilities. Nevertheless it remains to be investigated if

similar results can be obtained with bilinguals speaking two languages having the same number-words structure or with bilinguals speaking two highly transparent languages.

5. Conclusions

The present study revealed faster responses when adult bilinguals performed a transcoding task in their LM+ (i.e. German) compared to their LM- (i.e. French). Moreover, bilinguals' transcoding performance was slower and more error-prone in LM- compared to their monolingual French-speaking peers. This indicates that even in adulthood language of math acquisition influences simple numerical tasks such as transcoding, which complements similar findings in arithmetic and further strengthens the role of language in numerical cognition.

5. Bibliography

- Adesope, O. O., Lavin, T., Thompson, T., & Ungerleider, C. (2010). A Systematic Review and Meta-Analysis of the Cognitive Correlates of Bilingualism. *Review of Educational Research*, 80(2), 207–245. <https://doi.org/10.3102/0034654310368803>
- Archambeau, K., & Gevers, W. (2018). (How) Are Executive Functions Actually Related to Arithmetic Abilities? In *Heterogeneity of Function in Numerical Cognition* (pp. 337–357). Elsevier. <https://doi.org/10.1016/B978-0-12-811529-9.00016-9>
- Barrouillet, P. (2018). *Numerical Cognition and Memory(ies)*. *Heterogeneity of Function in Numerical Cognition*. Elsevier Inc. <https://doi.org/10.1016/B978-0-12-811529-9.00017-0>
- Barrouillet, P., Camos, V., Perruchet, P., & Seron, X. (2004). ADAPT: A Developmental, Asemantic, and Procedural Model for Transcoding From Verbal to Arabic Numerals. *Psychological Review*, 111(2), 368–394. <https://doi.org/10.1037/0033-295X.111.2.368>
- Bernardo, A. B. (2001). Asymmetric activation of number codes in bilinguals: further evidence for the encoding complex model of number processing. *Memory Cognition*, 29(7), 968–976. <https://doi.org/10.3758/BF03195759>
- Bialystok, E. (2009). Bilingualism: The good, the bad, and the indifferent. *Bilingualism: Language and Cognition*, 12(01), 3. <https://doi.org/10.1017/S1366728908003477>
- Blanken, G., Dorn, M., & Sinn, H. (1997). Inversion errors in Arabic number reading: Is there a nonsemantic route? *Brain and Cognition*, 34(3), 404–423. <https://doi.org/10.1006/brcg.1997.0917>

Campbell, J., & Epp, L. (2004). An encoding-complex approach to numerical cognition in Chinese-English bilinguals. *Canadian Journal of Experimental Psychology = Revue Canadienne de Psychologie Experimentale*, 58(4), 229–44. <https://doi.org/10.1037/h0087447>

Cohen, J., Mac Whinney, B., Flatt, M., & Provost, J. (1993). PsyScope: An interactive graphic system for designing and controlling experiments in the psychology laboratory using Macintosh computers. *Behavior Research Methods, Instruments, and Computers*, 25(2), 257–271.

de Bruin, A., Treccani, B., & Della Sala, S. (2015). Cognitive Advantage in Bilingualism: An Example of Publication Bias? *Psychological Science*, 26(1), 99–107.
<https://doi.org/10.1177/0956797614557866>

Dehaene. (1992). Varieties of numerical abilities. *Cognition*, 44, 1–42.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is Numerical Comparison Digital? Analogical and Symbolic Effects in Two-Digit Number Comparison. *Journal of Experimental Psychology: Human Perception and Performance*, 16(3), 626–641. Retrieved from
<https://core.ac.uk/download/pdf/22868005.pdf>

Geary, D. C., Cormier, P., Goggin, J. P., Estrada, P., & Lunn, M. C. E. (1993). Mental Arithmetic: A Componential Analysis of Speed-of-Processing Across Monolingual, Weak Bilingual, and Strong Bilingual Adults. *International Journal of Psychology*, 28(2), 185–201.
<https://doi.org/10.1080/00207599308247184>

Gelman, R., & Butterworth, B. (2005). Number and language: How are they related? *Trends in Cognitive Sciences*. <https://doi.org/10.1016/j.tics.2004.11.004>

Göbel, S. M., Moeller, K., Pixner, S., Kaufmann, L., & Nuerk, H. C. (2014). Language affects symbolic arithmetic in children: The case of number word inversion. *Journal of Experimental Child Psychology*, 119(1), 17–25. <https://doi.org/10.1016/j.jecp.2013.10.001>

Grosjean, F. (2010). *Bilingual: Life and Reality*. Harvard University Press.

Guijarro-Fuentes, P., Larranaga, M. P., & Clibbens, J. (2008). *First Language Acquisition of Morphology and Syntax (ed.)*. *Language Acquisition and Language Disorders LALD*. Retrieved from https://books.google.lu/books?hl=fr&lr=&id=0aU5AAAAQBAJ&oi=fnd&pg=PA269&ots=nir7jn-OgL&sig=kHVKzY1uvVSoFzUXo3GuFINrhms&redir_esc=y#v=onepage&q&f=false

HAHN, C. G. K., SAALBACH, H., & GRABNER, R. H. (2017). Language-dependent knowledge acquisition: investigating bilingual arithmetic learning. *Bilingualism: Language and Cognition*, 22(1), 47–57. <https://doi.org/10.1017/S1366728917000530>

Hartanto, A., Yang, H., & Yang, S. (2018). Bilingualism positively predicts mathematical competence: Evidence from two large-scale studies. *Learning and Individual Differences*, 61(October 2016), 216–227. <https://doi.org/10.1016/j.lindif.2017.12.007>

Helmreich, I., Zuber, J., Pixner, S., Kaufmann, L., Nuerk, H.-C., & Moeller, K. (2011). Language Effects on Children's Nonverbal Number Line Estimations. *Journal of Cross-Cultural Psychology*, 42(4), 598–613. <https://doi.org/10.1177/0022022111406026>

JASP Team. (2018). JASP Version 0.9 Computer Software. Retrieved from <https://jasp-stats.org/>

Lemer, C., Dehaene, S., Spelke, E., & Cohen, L. (2003). Approximate quantities and exact

number words: Dissociable systems. *Neuropsychologia*. [https://doi.org/10.1016/S0028-3932\(03\)00123-4](https://doi.org/10.1016/S0028-3932(03)00123-4)

Lin, J. F. L., Imada, T., & Kuhl, P. K. (2012). Mental addition in bilinguals: An fMRI study of task-related and performance-related activation. *Cerebral Cortex*, 22(8), 1851–1861. <https://doi.org/10.1093/cercor/bhr263>

Lonnemann, J., & Yan, S. (2015). Does number word inversion affect arithmetic processes in adults? *Trends in Neuroscience and Education*, 4(1–2), 1–5. <https://doi.org/10.1016/j.tine.2015.01.002>

Macizo, P., & Herrera, A. (2010). Two-digit number comparison: Decade-unit and unit-decade produce the same compatibility effect with number words. *Canadian Journal of Experimental Psychology*, 64(1), 17–24. <https://doi.org/10.1037/a0015803>

Macizo, P., Herrera, A., Paolieri, D., & Román, P. (2010). Is there cross-language modulation when bilinguals process number words? *Applied Psycholinguistics*, 31(04), 651–669. <https://doi.org/10.1017/S0142716410000184>

Macizo, P., Herrera, A., Román, P., & Martín, M. C. (2011). The processing of two-digit numbers in bilinguals. *British Journal of Psychology*, 102(3), 464–477. <https://doi.org/10.1111/j.2044-8295.2010.02005.x>

Mägiste, E. (1980). Arithmetical calculations in monolinguals and bilinguals. *Psychological Research*, 42(4), 363–373. <https://doi.org/10.1007/BF00308732>

Marian, V., & Fausey, C. M. (2006). Language-dependent memory in bilingual learning. *Applied*

Cognitive Psychology, 20(8), 1025–1047. <https://doi.org/10.1002/acp.1242>

Miura, I. T., Okamoto, Y., Kim, C. C., Chang, C.-M., Steere, M., & Fayol, M. (1994). Comparisons of Children's Cognitive Representation of Number: China, France, Japan, Korea, Sweden, and the United States. *International Journal of Behavioral Development*, 17(3), 401–411. <https://doi.org/10.1177/016502549401700301>

Morton, J. B., & Harper, S. N. (2007). What did Simon say? Revisiting the bilingual advantage. *Developmental Science*, 106, 719–726. <https://doi.org/10.1111/j.1467-7687.2007.00623.x>

Müller, N., & Pillunat, A. (2008). *Balanced bilingual children with two weak languages: A French/German case study. First language acquisition of morphology and syntax: perspectives across languages and learners*. John Benjamins Publishing.

Nuerk, H.-C., Kaufmann, L., Zoppoth, S., & Willmes, K. (2004). On the development of the mental number line: more, less, or never holistic with increasing age? *Developmental Psychology*, 40(6), 1199–1211. <https://doi.org/10.1037/0012-1649.40.6.1199>

Nuerk, H.-C., Weger, U., & Willmes, K. (2002). A unit-decade compatibility effect in German number words. *Current Psychology Letters: Behaviour, Brain & Cognition*, 7(2002/1, 7), 19–38. Retrieved from <http://cpl.revues.org/149>

Nuerk, H. C., Weger, U., & Willmes, K. (2001). Decade breaks in the mental number line? Putting the tens and units back in different bins. *Cognition*, 82(1). [https://doi.org/10.1016/S0010-0277\(01\)00142-1](https://doi.org/10.1016/S0010-0277(01)00142-1)

Nuerk, H. C., Weger, U., & Willmes, K. (2005). Language effects in magnitude comparison:

Small, but not irrelevant. *Brain and Language*, 92(3), 262–277.

<https://doi.org/10.1016/j.bandl.2004.06.107>

Paap, K. R. (2014, April 3). The role of componential analysis, categorical hypothesising, replicability and confirmation bias in testing for bilingual advantages in executive functioning. *Journal of Cognitive Psychology*. Routledge. <https://doi.org/10.1080/20445911.2014.891597>

Paap, K. R. (2016). The neuroanatomy of bilingualism: will winds of change lift the fog? *Language, Cognition and Neuroscience*. <https://doi.org/10.1080/23273798.2015.1082607>

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive Psychology*, 66(2), 232–258.
<https://doi.org/10.1016/j.cogpsych.2012.12.002>

Paap, K. R., Johnson, H. A., & Sawi, O. (2015). Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, 69, 265–78.
<https://doi.org/10.1016/j.cortex.2015.04.014>

Paap, K. R., Johnson, H. A., & Sawi, O. (2016, January 1). Should the search for bilingual advantages in executive functioning continue? *Cortex*. Elsevier.
<https://doi.org/10.1016/j.cortex.2015.09.010>

Paap, K. R., Myuz, H. A., Anders, R. T., Bockelman, M. F., Mikulinsky, R., & Sawi, O. M. (2017). No compelling evidence for a bilingual advantage in switching or that frequent language switching reduces switch cost. *Journal of Cognitive Psychology*, 29(2), 89–112.
<https://doi.org/10.1080/20445911.2016.1248436>

Pica, P., Lemer, C., Izard, V., & Dehaene, S. (2004). Exact and approximate arithmetic in an Amazonian indigene group. *Materials and Method. Science*, 306(5695), 1–16.

<https://doi.org/10.1126/science.1102085>

Poncin, A., Van Rinsveld, A., & Schiltz, C. (n.d.). Units first or tens first: Does language matter when processing visually presented two-digit numbers?

Prior, A., Katz, M., Mahajna, I., & Rubinsten, O. (2015). Number word structure in first and second language influences arithmetic skills. *Frontiers in Psychology*, 6(MAR), 266.

<https://doi.org/10.3389/fpsyg.2015.00266>

Proios, H., Weniger, D., & Willmes, K. (2002). Number representation deficit: a bilingual case of failure to access written verbal numeral representations. *Neuropsychologia*, 40(13), 2341–2349. [https://doi.org/10.1016/S0028-3932\(02\)00085-4](https://doi.org/10.1016/S0028-3932(02)00085-4)

Rugani, R., Regolin, L., & Vallortigara, G. (2008). Discrimination of small numerosities in young chicks. *Journal of Experimental Psychology. Animal Behavior Processes*, 34(3), 388–399. <https://doi.org/10.1037/0097-7403.34.3.388>

Saalbach, H., Eckstein, D., Andri, N., Hobi, R., & Grabner, R. H. (2013). When language of instruction and language of application differ: Cognitive costs of bilingual mathematics learning. *Learning and Instruction*, 26, 36–44. <https://doi.org/10.1016/j.learninstruc.2013.01.002>

Salillas, E., & Wicha, N. Y. Y. (2012). Early Learning Shapes the Memory Networks for Arithmetic: Evidence From Brain Potentials in Bilinguals. *Psychological Science*.

<https://doi.org/10.1177/0956797612446347>

Sittig, O. (1921). Störung des Ziffernschreibens und Rechnens bei einem Hirnverletzten.

European Neurology, 49(5), 299–306. <https://doi.org/10.1159/000190644>

Spelke, E. S., & Tsivkin, S. (2001). Language and number: A bilingual training study. *Cognition*, 78(1), 45–88. [https://doi.org/10.1016/S0010-0277\(00\)00108-6](https://doi.org/10.1016/S0010-0277(00)00108-6)

Stocco, A., & Prat, C. S. (2014). Bilingualism trains specific brain circuits involved in flexible rule selection and application. *Brain and Language*, 137, 50–61.
<https://doi.org/10.1016/j.bandl.2014.07.005>

Tellegen, P. J., Laros, J. A., & Petermann, F. (2012). *Non-verbaler Intelligenztest für Kinder und Erwachsene: SON-R 6-40*. Hogrefe.

Van Rinsveld, A., Brunner, M., Landerl, K., Schiltz, C., & Ugen, S. (2015). The relation between language and arithmetic in bilinguals: insights from different stages of language acquisition. *Frontiers in Psychology*, 6(March), 1–15. <https://doi.org/10.3389/fpsyg.2015.00265>

Van Rinsveld, A., Dricot, L., Guillaume, M., Rossion, B., & Schiltz, C. (2017). Mental arithmetic in the bilingual brain: Language matters. *Neuropsychologia*, 101, 17–29.
<https://doi.org/10.1016/j.neuropsychologia.2017.05.009>

Venkatraman, V., Siong, S. C., Chee, M. W. L., & Ansari, D. (2006). Effect of language switching on arithmetic: a bilingual fMRI study. *Journal of Cognitive Neuroscience*, 18(1), 64–74. <https://doi.org/10.1162/089892906775250030>

Volmer, E., Grabner, R. H., & Saalbach, H. (2018). Language switching costs in bilingual mathematics learning: Transfer effects and individual differences. *Zeitschrift Für*

Erziehungswissenschaft, 21(1), 71–96. <https://doi.org/10.1007/s11618-017-0795-6>

von Bastian, C. C., Souza, A. S., & Gade, M. (2016). No evidence for bilingual cognitive advantages: A test of four hypotheses. *Journal of Experimental Psychology: General*, 145(2), 246–258. <https://doi.org/10.1037/xge0000120>

Wang, Y., Lin, L., Kuhl, P., & Hirsch, J. (2007). Mathematical and Linguistic Processing Differs Between Native and Second Languages: An fMRI Study. *Brain Imaging and Behavior*, 1(3–4), 68–82. <https://doi.org/10.1007/s11682-007-9007-y>

Xu, F., Spelke, E. S., & Goddard, S. (2005). Number sense in human infants. *Developmental Science*, 8(1), 88–101. <https://doi.org/10.1111/j.1467-7687.2005.00395.x>

Footnotes

- ¹ <http://www.men.public.lu/catalogue-publications/systeme-educatif/langues-ecole-luxembourgeoise/reajustement-enseignement-langues/fr.pdf>, p. 45

Table:

Table 1.

	Simultaneous				Tens-First				Units-First			
	BIFR	BIGE	FR	GE	BIFR	BIGE	FR	GE	BIFR	BIGE	FR	GE
Mean	3.486	2.296	1.499	2.692	3.486	3.061	1.675	2.381	3.401	2.891	2.293	2.381
Std. Deviation	2.709	2.933	2.570	3.235	2.933	3.165	1.961	2.588	3.575	2.776	3.131	3.866

Table 1. Descriptive statistics of errors by condition for each language profile in percent.

Abbreviations BI, FR and GE correspond respectively to Bilingual, French and German groups.

Figures

Figure 1

Figure 1. *Transcoding paradigm: Participants heard a two-digit number via headsets and had to match it with the corresponding Arabic two-digit number. Arabic numbers were presented directly after the sound file ended with different orders of unit- and ten-digit appearance, yielding three different conditions: “simultaneous”, “tens-first”, and “units-first” (left to right). Response alternatives consisted of: Ten-distractor; Unit-distractor; Match; Inversion-distractors (top to bottom for illustrative purposes here, random positions during the experiment).*

Figure 2.*(a)* *(b)* *(c)*

Figure 2. Transcoding speed as a function of conditions (“simultaneous”, “tens-first” and “units-first”) and language profile (hatched lines represent the Bilinguals group and plain lines

represent the Monolingual group. Blue line represent French-speakers and dark lines represent German-speakers). Error bars depict the standard errors