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# The role of general executive functions in receptive language switching and monitoring*

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*We assessed language switch and mixing costs in a language-general semantic categorization task and examined how these costs relate to general inhibition and set shifting capacities. The participants were 51 native Finnish subjects with English as L2. The results showed significant symmetric language switch costs and, unexpectedly, a mixing advantage in L2: reaction times were faster in the mixed language block than in the single language block. The interactions with the general executive functions showed no consistent overall pattern. We argue that the L2 mixing advantage stems from statistical facilitation in line with a horse race model, or from opportunistic planning as suggested by the Adaptive Control hypothesis. We argue that the results overall indicate that lexical access in language reception is non-selective.*

Keywords: semantic categorization, language switching, language mixing, asymmetric switch cost, asymmetric mixing advantage, BIA model, BIA+ model, Adaptive Control hypothesis, Inhibitory Control model, Horse Race model, inhibition, set-shifting

## 1. Introduction

A central problem in understanding bilingual language processing is how bilinguals succeed in processing only one language without interference from the other languages they are proficient in. This problem is highlighted by the fact that the lexicon of a bilingual appears to be an integrated one, with words of both languages being represented in the same mental lexicon (e.g., van Heuven & Dijkstra, 2010). How a bilingual is able to select words of the targeted language and not their translational equivalents is sometimes called the ‘hard problem’ of bilingual psycholinguistics (Finkbeiner, Almeida, Janssen & Caramazza, 2006). Lexical control has been studied quite extensively in language production, but less so in reception. In this study, we will focus on lexical control processes in reception from the point of view of language switching. In particular, we will examine the role of executive functions in receptive language switching.

In cued naming tasks, switching between languages typically causes a processing cost, assumed to reflect the effort needed to access the target language. The switch

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cost is typically higher when switching into the dominant L1 than when switching into the weaker L2 (Bobb & Wodniecka, 2013). This asymmetry is often explained in terms of inhibition. According to the *Inhibitory Control* (IC) model (Green, 1998), the non-target language is inhibited to avoid its intrusion into the target language. The model implies that the dominant L1 has to be inhibited more strongly during L2 production than the weaker L2 during L1 production. This stronger inhibition of L1 has to be resolved when switching from L2 to L1, causing a larger switch cost for L1 than L2. The asymmetry could, however, also stem from other sources than inhibition. For example, the *Activation Model* (Philipp, Gade & Koch, 2007) suggests that the weaker L2 requires more activation in language production than the stronger L1. Thus, when switching from L2 to L1, the activation of L2 has to be resolved so that it does not disrupt L1 production, causing a larger cost when switching into L1 than L2.

Both the IC and the Activation model thus have in common that, in language production, target words are selected through top-down modulation of the activation levels of the lexical representations. This modulation is typically considered to be performed by the general executive system (Green, 1998; Meuter & Allport, 1999). The studies that have directly addressed the role of executive functions (particularly inhibition) in language switching during production have, however, yielded inconsistent results (see Jylkkä, Lehtonen, Lindholm, Kuusakoski & Laine, in press; Linck, Schwieter & Sunderman, 2012).

Peeters, Runnqvist, Bertrand, and Grainger (2014) suggest that while the locus of control in language production is endogenous (the speaker could produce a word in either language but intends to use only the target language), in reception it is exogenous: the language one is seeing or hearing has distinctive orthographic/phonological features that sets it apart from other languages. These language-specific features activate the lexical representations of the corresponding language in a bottom-up manner, lessening the need for endogenous control processes. In fact, various studies indicate that in reception, lexical access is non-selective, that is, the features of a stimulus can activate the lexical representations of any language the speaker is proficient in. For instance, van Heuven, Dijkstra, and Grainger (1998) found that in bilinguals, orthographic neighbors (words in two languages that differ from each other by a single letter) elicited significant interference in a lexical decision task both within and across languages. Moreover, cross-language but not within-language interference disappeared when testing monolingual participants (de Groot, Delmaar & Lupker, 2000; Dijkstra, Grainger & van Heuven, 1999; Duyck, Assche, Drieghe & Hartsuiker, 2007; van Hell & Dijkstra, 2002). This suggests that stimuli can activate lexical representations of both languages a bilingual is proficient in.[1]

Studies supporting non-selective access have typically utilized lexical decision and compared behavioral responses to homographs and orthographic neighbors. The language switching paradigm utilized here provides a different viewpoint to lexical control processes, as it focuses on the effect of language switching per se, irrespective of the possible effect of orthographic features. The receptive language switching studies have typically discovered a language switch cost, particularly in lexical decision tasks (e.g., Grainger & Beauvillain, 1987; von Studnitz & Green, 1997; Thomas & Allport, 2000). A switch cost is less often discovered in semantic categorization, and its magnitude is smaller (e.g., Macizo, Bajo & Paolieri, 2012; von Studnitz & Green, 2002).

In the present study we will examine the mechanisms underlying receptive language switching and mixing, and in particular whether general executive functions have any role in this process. In language production, the IC model posits a central role to executive inhibition in lexical access. Here we will examine whether a similar process could be at play in language reception as well. This question has rarely been addressed before, possibly because of the aforementioned studies indicating that lexical access in language reception is non-selective and exogenously driven, apparently leaving no room for executive inhibition. However, it is unclear why switch costs would occur at all in language reception if lexical access were wholly non-selective. The mechanisms underlying receptive switch costs are not known. Prominent theoretical models of language reception have been formulated mainly on the basis of findings such as interlingual homograph and orthographic/phonological neighborhood effects, with little or no emphasis on language switching. We will next examine the theoretical models of language reception, how they could account for language switch costs, and what their implications for the role of general executive functions in language switching are.

### *1.1. Models of lexical selection and switch costs in reception*

The Bilingual Interactive Activation (BIA; Dijkstra & van Heuven, 2002) model holds that lexical representations are connected to a language node, such that each lexical representation of a language L has an excitatory connection to the L language node, which in turn facilitates all the L words and inhibits all the L* words. This proposal bears thus some similarity to the IC model,

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[1] Although these studies indicate that lexical access in reception is non-selective, inhibition within the lexicon may be required to resolve possible conflict between homographs (see Martín, Macizo, & Bajo, 2010).

albeit in the BIA model the inhibitory process is within the lexicon and not governed by the general executive system. It could be argued that in a receptive switching paradigm, the BIA model implies a switch cost. This is because on an L switch trial (preceded by an L* trial), the L-node has received inhibition from an L* word active during the previous trial, and this inhibition has to be resolved before L can be activated (cf. Grainger, Midgley & Holcomb, 2010).

In line with the BIA model, most studies to date have found a symmetric switch cost in lexical decision (Grainger & Beauvillain, 1987; Studnitz & Green, 1997; Thomas & Allport, 2000) and in semantic categorization (e.g., Macizo, Bajo & Paolieri, 2012; von Studnitz & Green, 2002). Jackson, Swainson, Mullin, Cunnington, and Jackson (2004), on the other hand, found an asymmetric switch cost in a semantic categorization task, with a larger switch cost for L1 than L2. This finding can be interpreted along the lines of the BIA model provided that one assumes that the inhibitory connections between the language nodes are stronger from L2 to L1 than vice versa. This could be because the stronger L1 needs to be suppressed more in order to process the weaker L2.

The Bilingual Interactive Activation Plus (BIA+) model is a revised version of the BIA model (Dijkstra & Van Heuven, 2002; Van Heuven & Dijkstra, 2010). It eliminates the role of the language nodes in modulating lexical activation and postulates a distinct word identification system and a task-decision system. The assumption that the language nodes do not modulate lexical activation is mainly based on evidence of non-selective access, such as inter-language semantic priming (e.g., De Bruijn, Dijkstra, Chwilla & Schriefers, 2001) and cognate facilitation effects (Duyck et al., 2007). If the two languages of a bilingual have inhibitory connections through the language nodes as the BIA model suggests, then these priming and facilitation effects should not be present, or at least they should be smaller in a bilingual than in a monolingual context (cf. van Heuven & Dijkstra, 2010). A central assumption in the BIA+ model is that lexical access is wholly non-selective. The BIA+ poses only few restrictions on lexical access; for example, it implies that sentence context restricts the plausible candidates for selection based on syntax. The task-decision system (TDS) is another novel component in BIA+ compared to its predecessor. The TDS receives input from the word identification system (WIS), but the connection is unidirectional. The function of the TDS is mainly to map the output from the WIS to a behavioral response. Thus, the BIA+ differs from the IC model in that lexical activation is unaffected by the TDS.

How does the BIA+ model account for switch costs in receptive tasks? To answer this question, we must first distinguish between language-specific and language-general receptive tasks. In the former, the response depends on the language of the stimulus (e.g., determine whether the stimulus is a real word in language L), whereas in the latter, the response is independent of stimulus language (e.g., determine whether the stimulus is a real word in any language; cf. von Studnitz & Green, 1997). The difference between these two types of tasks can be understood in terms of *language task schemas* which map stimuli to responses. In a language-specific task where the subject has to respond differently to the stimuli of the two languages, two language task schemas are needed, whereas in a language-general task where the response is independent of language, only one language task schema is needed. There is evidence that a language switch cost is larger in language-specific tasks than in language-general tasks (e.g., von Studnitz & Green, 1997). The BIA+ model can account for switch costs in language-specific tasks through switching between task schemas that is performed by the TDS. This is a general set shifting process, not specific to language tasks (cf. Rogers & Monsell, 1995).

Switch costs have also been found in language-general tasks (Jackson et al., 2004; Macizo et al., 2012; von Studnitz & Green, 1997, 2002). In these cases there is no shifting of task schemas, only the stimulus language shifts. How would the BIA+ model account for language switch costs in these cases? Dijkstra and van Heuven (2002) propose altogether five possible sources of switch costs in language-general tasks: (i) the task and its associated response bindings, (ii) the actual response, (iii) item language, (iv) between-trial adaptations for the relative recognition thresholds for the two languages, and (v) attention shifts between stimulus-to-response mappings between languages. To briefly evaluate each of these, (i) response bindings associated with the task account for switch costs in receptive tasks that engage two or more language task schemas. In a language-general task, however, the task and its response bindings do not shift. The actual response (ii) is of the same type irrespective of stimulus language. Item language (iii) can arguably cause a main effect of language, as according to BIA+ the weaker L2 has lower baseline activation. However, this difference in baseline activation does not affect the switch costs, which are defined as the difference between switch and repetition trials within a language. Suggestion (iv) about between-trial adaptations in recognition thresholds is somewhat problematic, as Dijkstra and van Heuven do not specify how these adaptations would be realized: the BIA+ model does not involve inhibitory connections between language nodes as its predecessor BIA does, so these cannot account for any possible recognition threshold dynamics. Possible attention shifts between stimulus-to-response bindings (v) are not relevant in language-general tasks where the stimulus-to-response binding is independent of the stimulus language and should not affect language switch costs. In sum, the BIA+ model arguably does not explain switch costs in language-general receptive tasks.

### *1.2. The role of executive functions in receptive language switching*

The BIA and BIA+ models do not postulate a role to executive functions in lexical access in language reception. We will next briefly examine some of the experiments in the receptive literature that (directly or indirectly) address the role of general inhibition in receptive language switching.

In their classic study, Grainger and Beauvillain (1987) found that switch costs in an English-French lexical decision task were eliminated with the introduction of language-specific orthographic cues, which they took to indicate that the switch cost stems from within the bilingual lexicon, that is, from word recognition processes. However, Thomas and Allport (2000) note that Grainger and Beauvillain's study was lacking a control condition, as the orthographic cues were only included in the real words and not in the nonwords, making it possible that the subjects made the lexical decision based on the presence of orthographic cues with no need to access lexical information at all. Thomas and Allport (2000) found that when the orthographic cues were included in both words and nonwords, a switch cost was present. They take this to indicate that the switch cost does not stem from within the lexicon, but outside of it. These results do not support the BIA and BIA+ models where language-specific orthographies would hypothetically activate only items in the target language. The results leave open the possibility that switch costs are affected by top-down modulation of lexical activation, as suggested by the IC model in production.

Next we turn to two event-related potential (ERP) studies which address the role of general EF in receptive language switching. Jackson et al. (2004) discovered an asymmetric switch cost in reaction times in a language-general parity judgment task with number words, with larger costs when switching into the dominant L1 (English) compared to the weaker L2 (French, German, or Spanish). This behavioral finding is in line with the IC model, which implies that the dominant L1 is inhibited to avoid its intrusion to the weaker L2, causing a larger switch cost for L1 than for L2. However, Jackson et al. (2004) also examined the differences in ERP responses between switch and repetition trials. In an earlier production study (Jackson, Swainson, Cunnington & Jackson, 2001), they had found enhanced N2 potential over frontal sensor sites for L2 switch trials, a response that was previously also found for response suppression tasks and could therefore reflect executive L1 suppression. In the reception task, no such ERP effect was found. This could indicate that the observed switch cost was not due to general inhibition, in contrast to the IC model. Rather, these results are in line with the BIA model where switch costs stem from within the lexicon.

The results of Pellikka, Helenius, Mäkelä, and Lehtonen (2015), in turn, can be taken to support the hypothesis that inhibition plays a role in receptive language switching. Using a language-general semantic categorization task, they found enhanced N400m responses for L1 words in an L2 context, compared to L2 words in an L1 context. As the N400m response is typically taken to reflect lexical access, the results suggest that L1 items in L2 context are more difficult to access than L2 items in an L1 context. Pellikka et al. (2015) take this to indicate that the stronger language is inhibited in an L2 context. However, the results leave open the locus of inhibition.

### *1.3. The present study*

Thus, based on outcomes of previous studies the role of general EF and particularly inhibition in receptive language switching is still unclear. In the present study, our aim was to shed light on this question by examining the mediating effect of general inhibitory and set shifting capacity on language switch and mixing costs in a language-general semantic categorization task. Inhibition was assessed with the Simon and Flanker tasks, and set shifting capacity with the number-letter task. To our knowledge, the role of general executive functions has not yet been examined in the receptive domain.

Another novel feature of the present experiment is that, in addition to mixed language blocks, we utilized single language blocks. This enables assessing in what way lexical access processes differ in mixed vs. single language contexts. Mixed vs. single block comparisons can be expected to yield mixing costs, which can be considered to reflect monitoring demands or inhibition present in the mixed block. A mixing cost is defined as the performance difference between mixed block repetition trials and single block trials. Although in both types of trials the language does not shift, it can be hypothesized that in the mixed block repetition trials monitoring for possible language switches or sustained inhibition is present, causing longer reaction times and higher error rates.

The BIA model predicts a switch cost in the semantic categorization task due to the inhibitory connections between the language nodes, as well as a mixing cost due to stronger language inhibition in the mixed block than in the single block. According to the BIA model, the switch or mixing cost is not mediated by the subject's general inhibitory capacity, as inhibition takes place at the lexical level through the language nodes. The BIA+ model, in turn, arguably predicts neither a switch nor a mixing cost in the semantic categorization task, as it assumes that lexical access is wholly non-selective.

Our main interest in the experiment was to examine the possible role of general executive inhibition in language reception. This question is motivated by the results of Pellikka et al. (2015), which indicate that inhibition may be employed in receptive language switching, similarly as the IC model implies in the production domain. The IC model predicts that the stronger L1 is inhibited more than the weaker L2 to facilitate the processing of the weaker language, leading to switch cost asymmetry: on an L1 switch trial, L1 inhibition from the previous L2 trial has to be resolved in order for the L1 items to be activated, causing a larger switch cost into L1 than L2. The IC model predicts that the switch costs and asymmetry should correlate with a subject's general inhibitory capacity (cf. Linck et al., 2012). Moreover, the IC model implies a mixing cost, due to the inhibition that should be present in the mixed block but absent in the single blocks. The mixing cost should also be asymmetric, as L1 is more strongly inhibited in the mixed block than L2. The mixing cost should likewise correlate with the subject's inhibitory capacity.

In addition to assessing the relationship between the inhibitory effects and the language switch and mixing costs, an unplanned analysis was conducted to examine the main effect of inhibitory capacity on overall performance in the mixed vs. single blocks. This was done to assess the Adaptive Control hypothesis (Green & Abutalebi, 2013), which would predict that interference control is central in single language contexts but not in mixed language contexts (see Discussion).

Finally, we examined the relationship between the language switch and mixing costs and a subject's general set shifting capacity, as measured with the number-letter task. In language production, Meuter and Allport (1999) suggest that language switching engages general set shifting processes, although evidence for this proposal is somewhat inconsistent (Jylkkä et al., in press; Cattaneo et al., 2015; Liu, Fan, Rossi, Yao & Chen, 2015; Prior & Gollan, 2011, 2013). We hypothesized that if receptive language switching and mixing engage similar general executive processes, then the language switch and mixing costs would correlate with the respective cost effects in the number-letter task.

## 2. Method

### *2.1. Participants*

The participants were 51 neurologically healthy native speakers of Finnish (33 females) recruited via e-mail lists at the Abo Akademi University and the University of Turku, both in Finland. They had learned L2 (English) mainly in elementary school as their first foreign language, at the age of 9 or 10. The home language of all participants was Finnish, and L1 (Finnish) was learned from birth. The participants self-estimated their proficiency regarding reading, writing, speaking, and listening on a scale from 1 to 7, where 7 represents native-level proficiency. The participants reported higher proficiency in Finnish than in English on all the measures (*Z*'s > 5.5). L2 proficiency was assessed with an online test where they were presented with English words and pseudowords and they had to decide whether the letter string is a true English word or not. The test has been developed by the Ghent University Center for Reading Research and is available online at http://vocabulary.ugent.be. The score of the participants on this test was on average 58 (*SD* = 11.8, range 31 – 80) on a 1 – 100 scale, i.e., they knew approximately 58% of the English words. Key participant characteristics are reported in Table 1.

Table 1. *Participant characteristics and self-ratings*

| | L1 | | L2 | |
|---|---|---|---|---|
| | Mean (SD) | Range | Mean (SD) | Range |
| Age | 28.6 (7.0) | 19-51 | – | – |
| Age of acquisition | 0 (0) | 0 | 9.1 (1.6) | 4-13 |
| Self-ratings of ability (1-7) | | | | |
| Reading | 7.0 (.14) | 6-7 | 5.9 (.64) | 4-7 |
| Writing | 6.9 (.34) | 5-7 | 5.7 (.83) | 4-7 |
| Speaking | 7.0 (.14) | 6-7 | 5.8 (.79) | 4-7 |
| Listening | 7.0 (.20) | 6-7 | 5.9 (.65) | 4-7 |
| Overall | 7.0 (.12) | 6.5-7 | 5.9 (.60) | 4.5-7 |

### *2.2. Procedure*

The current experiment was part of a larger project investigating the mediating effects of general executive performance on language switch and mixing costs in both language production and reception. The results from the production task are reported elsewhere (Jylkkä et al., in press). Each participant was tested in a single session that took ca 1.5 hours. Participants first filled in an informed consent form and then a background information form that probed, among other things, their language and educational background and possible neurological and psychiatric conditions. Then the participants performed the receptive and productive language switching tasks. The semantic categorization task included three blocks, Finnish and English single language blocks and a mixed language block. The order of the blocks within the semantic categorization task was counterbalanced.

After the language switching tasks, the subjects were presented with the Bilingual Switching Questionnaire (Rodriguez-Fornells, Krämer, Lorenzo-Seva, Festman & Münte, 2012; not analyzed here), then the executive functions tests, followed by the L2 proficiency test. The executive functions (EF) tasks were the Simon (Simon & Rudell, 1967), Flanker (adapted from Eriksen & Eriksen, 1974), and the number-letter task (adapted from Rogers

& Monsell, 1995; for detailed descriptions of the EF tasks, see Appendix S1). The Simon and Flanker tasks yield inhibitory cost effects (the Simon and Flanker effect), defined as the difference between incongruent and congruent trials. The cost effects are higher the worse a subject's inhibitory capacity. The number-letter task yields two measures: the switching effect (NLSE) and the mixing effect (NLME). The NLSE is the cost produced by switching between the two tasks while the NLME is the difference between performance in the mixed block repetition trials and single block trials in the same task, typically considered as a monitoring cost. The order of the executive tasks was counterbalanced.

### 2.3. *The semantic categorization task*

In the semantic categorization task, the subject was to judge whether a word presented on a computer screen referred to an animate or inanimate object by pressing one of two keys. The subject was instructed to respond as fast and as accurately as possible. The response was given on a Cedrus$^{TM}$ response box which enables more accurate determination of reaction time than keyboard. A trial began with a fixation cross in the middle of the screen (500 ms), followed by the target word in either Finnish or English (1500 ms or until the subject responded), and then a blank interval (500 ms). The fixation cross and stimuli were presented in white on a black background.

The task consisted of L1 and L2 single blocks (90 trials each), and a mixed block (180 trials, consisting of the words of the single blocks). In the mixed block, there were 60 switch trials and 119 repetition trials (the first trial was neither a repetition nor a switch trial). There was an equal amount of L1 and L2 switch trials (30 each). The Finnish and English words were translational equivalents, matched in length in letters, lemma frequency, and bigram frequency ($p$'s $> .5$). In the mixed block, the language order was pseudorandomized so that there were never more than four same-language items in a row (that is, three repetition trials). Before each of the actual test blocks, the subject performed a practice version of the block, consisting of 10 trials for the single language blocks and 20 trials for the mixed block.

Table 2. *Correct reaction times and error rates in the EF tasks*

| | RT in ms | | Errors in % | |
|---|---|---|---|---|
| | M | SD | M | SD |
| **Simon task** | | | | |
| Congruent | 377 | 51 | 2.5 | 3.8 |
| Incongruent | 402 | 49 | 4.1 | 3.9 |
| Simon effect | 26 | 18 | 1.6 | 5.5 |
| **Flanker task** | | | | |
| Congruent | 407 | 47 | .3 | .9 |
| Incongruent | 474 | 47 | 4.7 | 4.7 |
| Flanker effect | 67 | 17 | 4.4 | 4.6 |
| **Number-letter task** | | | | |
| Single task trials | 524 | 82 | 2.6 | 3.0 |
| Repetition trials | 771 | 114 | 1.8 | 2.8 |
| Switch trials | 1046 | 226 | 4.4 | 4.4 |
| Switching cost | 280 | 131 | 2.7 | 4.6 |
| Mixing cost | 253 | 113 | −.8 | 3.8 |

Table 3. *Correct reaction times and error rates in the semantic categorization task by Language and Condition*

| | Language | |
|---|---|---|
| Condition | L1 | L2 |
| | Reaction times | |
| Switch | 657 (115) | 685 (109) |
| Repetition | 654 (103) | 680 (101) |
| Single language block | 656 (109) | 714 (117) |
| **Switch cost** | **3 (36)** | **5 (24)** |
| **Mixing cost** | **−2.1 (72)** | **−34 (79)** |
| | Error rate percentages | |
| Switch | 1.3 (2.5) | 2.3 (2.9) |
| Repetition | 1.6 (2.2) | 2.5 (2.7) |
| Single language block | 2.1 (1.9) | 2.5 (3.3) |
| **Switch cost** | **−.3 (2.6)** | **−.2 (3.6)** |
| **Mixing cost** | **−.5 (2.0)** | **−.1 (2.2)** |

## 3. Results

In both the semantic categorization and EF tasks, an individual's reaction time on a given trial was deleted as an outlier if it deviated more than three standard deviations from the individual's overall reaction time in that block. Moreover, if a subject's overall error rate exceeded 15% in any of the EF tasks or the semantic categorization task, his/her reaction times and error rates in that task were excluded from analysis. In the EF tasks, one subject was thus excluded in the Simon task, and two subjects in the number-letter task. No subjects were excluded in the semantic categorization task.

All the EF cost effects in log reaction times were significant and in the expected direction ($|t|(48\text{-}50)$'s $> 10$, $p$'s $< .001$). Also in the error rates, the effects were significant and in the expected direction on all measures ($|Z|$'s $> 2.6$, $p$'s $< .05$) except for the NLME ($|Z| = 1.8$, $p > .05$). The results of the EF tasks are summarized in Table 2.

Mean reaction times and error rates in the semantic categorization task are summarized in Table 3.

### *3.1. Switch and mixing costs*

Switch and mixing costs were examined using linear mixed models. The analyses were conducted in R using the package lme4 (Bates et al., 2015). The model included the log-transformed RT as a dependent variable, Condition (mixed block repetition, mixed block switch, and single block) and Language as predictors, and Subject and Stimulus as random effects. Normality of the trial log-RTs was inspected visually by using quantile-quantile plots for each subject and word separately. The log-RT distributions of two subjects had light tails, otherwise the log reaction times showed no serious violations of normality. No measures were taken to correct these deviations, as the reaction times were already log-transformed and there were no clear outliers. The plots for words showed no serious violations of normality. Visual investigation of the model residual plots did not show signs of heteroscedasticity or bias.

Using linear mixed models instead of ANOVAs has the advantage of simultaneously taking into account both between-subjects and between-items variation. Simple coding of categorical variables was utilized so that the model gives estimates for differences between levels of factors. The model estimates are contrasted against a baseline which can be changed to attain estimates for the different effects (note that changing the baseline does not affect overall model fit). For example, when baseline is set to L1 repetition trials, the estimate for *Switch* gives the switch cost in L1.

Estimates from the mixed effect model are summarized in Table 4. The row titled *Switch* in the table under the baseline (intercept) *Mixed block L1 repetition* shows the estimated difference between the baseline and switch trials. The positive estimate ($E = .012$, $t = 3.95$, $p < .001$) indicates that the subjects responded more slowly in the L1 switch trials than in the L1 repetition trials, thus showing a significant switch cost in L1 (see Figure 1). The back-transformed estimate of the size of this cost was 18 ms. The row titled *Single block* in Table 4 contrasts the baseline (Mixed block L1 repetition) against the single block L1 trials, and shows that there is no mixing cost in L1 ($E = .0029$, $t = 1.58$, $p > .05$).

Before going into the interactions, we present the main effects under the other three baselines. First, the baseline titled *Mixed block L2 repetition* was used to attain estimates of switch and mixing costs in L2. The row *Switch* under this baseline shows that the subjects took longer to respond to the switch trials than to the repetition trials in L2 ($E = .0081$, $t = 2.70$, $p < .01$), indicating a significant switch cost in L2. The back-transformed estimate of the switch cost was 14 ms. The row *Single block* shows that the subjects took longer to respond to the L2 single block trials than the L2 repetition trials, thus revealing a mixing advantage (i.e., a negative mixing cost) in L2. The back-transformed estimate for the L2 mixing advantage was 36 ms.

Table 4. *Estimated coefficients of the switch and mixing costs in the semantic categorization task*

| Fixed effects<br>Predictor | Estimate | SE | \|t\| |
|---|---|---|---|
| *Intercept: Mixed block L1 repetition* | *2.80* | *.0085* | *330.04**** |
| Switch | .012 | .0030 | 3.95*** |
| Single block | .0029 | .0018 | 1.58 |
| L2 | .016 | .0034 | 4.77*** |
| L2 × Switch | −.0039 | .0042 | .92 |
| L2 × Single block | .020 | .0026 | 7.74*** |
| *Intercept: Mixed block L2 repetition* | *2.82* | *.0085* | *331.91**** |
| Switch | .0081 | .0030 | 2.70** |
| Single block | .023 | .0018 | 12.51*** |
| *Intercept: Mixed block L1 switch* | *2.82* | *.0087* | *324.46**** |
| L2 | .012 | .0042 | 2.94** |
| *Intercept: L1 single block* | *2.81* | *.0084* | *332.71* |
| L2 | .036 | .0031 | 11.69*** |
| Random effects | Variance | SD | |
| Subject | .0034 | .058 | |
| Stimulus | .00033 | .018 | |
| Residual | .0050 | .058 | |

The two last baselines were switch trials in L1, and L1 single block, which were used to estimate the effect of language in these conditions. Responses to L2 words were slower in both conditions (see Table 4).

The two-way interactions *L2 × Switch* and *L2 × Single block* provide estimates for the asymmetric switch and mixing costs. The switch costs did not differ between the two languages ($p > .1$), but the mixing effects did ($E = .020$, $t = 7.74$, $p < .001$), reflecting a mixing advantage (negative mixing cost) in L2 but no mixing effect in L1.

#### *The L2 mixing advantage and repetition priming*

An additional analysis was conducted to rule out the possibility that the mixing advantage in L2 could be due to repetition priming. In the semantic categorization task, translation equivalents were used as stimuli. Thus, semantic priming may occur within the mixed block where each concept occurs twice (once in L1 and once in L2), possibly causing shorter reaction times than in the single block where each concept occurs only once (for the same

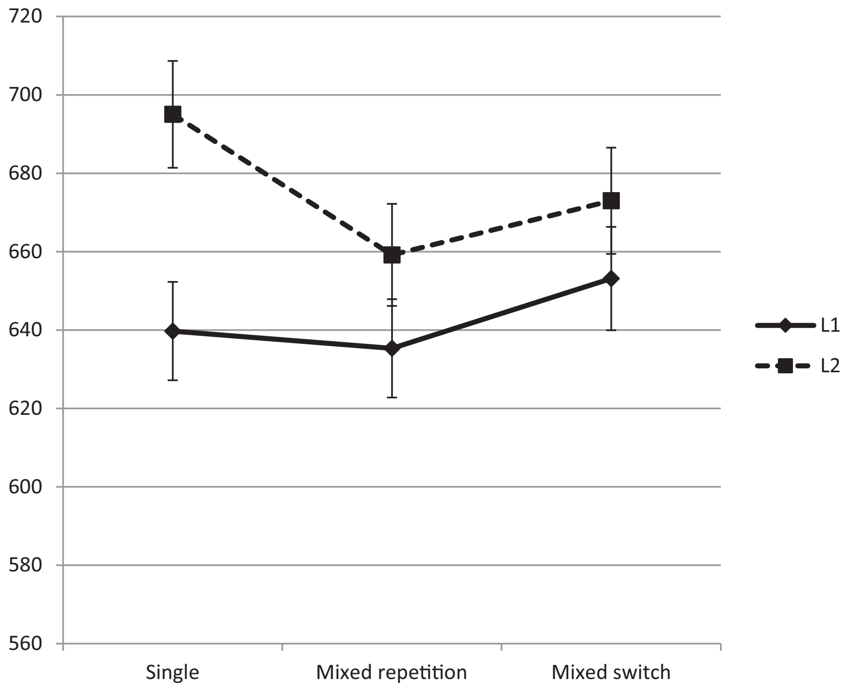

Figure 1. Switch and mixing cost estimates by Condition and Language. Error bars represent standard errors.

reason, priming also occurs between blocks, but this effect is eliminated by counterbalancing).

To examine the possible effect of within-mixed-block priming, a new Condition2 variable was created. The variable levels were the same as in Condition used earlier, but with the addition of a specification whether the concept occurrence was first or second.[2] The concept occurrence order was thus embedded in the Condition2 variable instead of adding it in the model as a separate variable. A separate variable for concept order would have been collinear with block type because in the single blocks all concept occurrences are first occurrences. The model included log-RT as dependent variable and Condition2 as predictor, and Subject and Stimulus as random factors. The model was run separately for L1 and L2, because including Language as a predictor caused rank deficiency issues due to insufficient data to conduct the analysis with both Language and Condition2, which had five levels.

In L1, RT for the first occurrence of a concept did not differ from its second occurrence in the mixed block repetition trials ($t = -.95, p > .1$), or in the mixed block switch trials ($t = -.86, p > .1$). In L2, the first occurrence of a concept did not differ from its second occurrence in the mixed block repetition trials ($t = -.067, p > .1$), but it did in the mixed block switch trials ($E = .0082$, $t = 2.13$, $p < .05$). However, in the L2 switch trials, the second occurrence of the concept was responded to slower than the first occurrence, which does not indicate repetition priming.

We additionally examined the mixing costs in this model to see if they occurred also between the first concept occurrences, to make sure that the mixed block advantage is not due to repetition priming. Separate analyses were conducted using data subsets for L1 and L2. Analyzing first concept occurrences only, there was no mixing effect in L1 ($t = .72, p > .1$), but there was a mixing advantage in L2 ($E = .023$, $t = 7.51$, $p < .001$). The strength of the L2 mixing advantage was very similar to that in the original analyses. In sum, there were no indications that the L2 mixing advantage would be due to repetition priming.

### *Unplanned analysis of the L2 mixing advantage in random subsamples*

We additionally tested the robustness of the L2 mixing advantage by randomly dividing the sample into two subsets of roughly equal size. Using the same models as in the original analyses, the L2 mixing cost was present in both subsamples.[3]

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[2] Thus, the variable had five levels: (1) mixed block repetition trials first concept occurrence (CO); (2) mixed block repetition trials second CO; (3) mixed block switch trials first CO; (4) mixed block switch trials second CO; and (5) single block (where all concepts occurred only once).

[3] In subsample A ($n = 25$), there was an L2 mixing advantage ($E = .014$, $t = 5.85$, $p < .001$), while none of the other main effects were significant. In subsample B ($n = 26$) we found a mixing advantage for both L1 ($E = .0085$, $t = 3.35$, $p < .001$) and L2 ($E = .028$, $t = 11.06$, $p < .001$). The mixing advantage was significantly larger for L2 ($E = -.020$, $t = 5.48$, $p < .001$). Moreover, in subsample B there was a switch cost in L1 ($E = .010$, $t = 2.53$, $p < .05$).

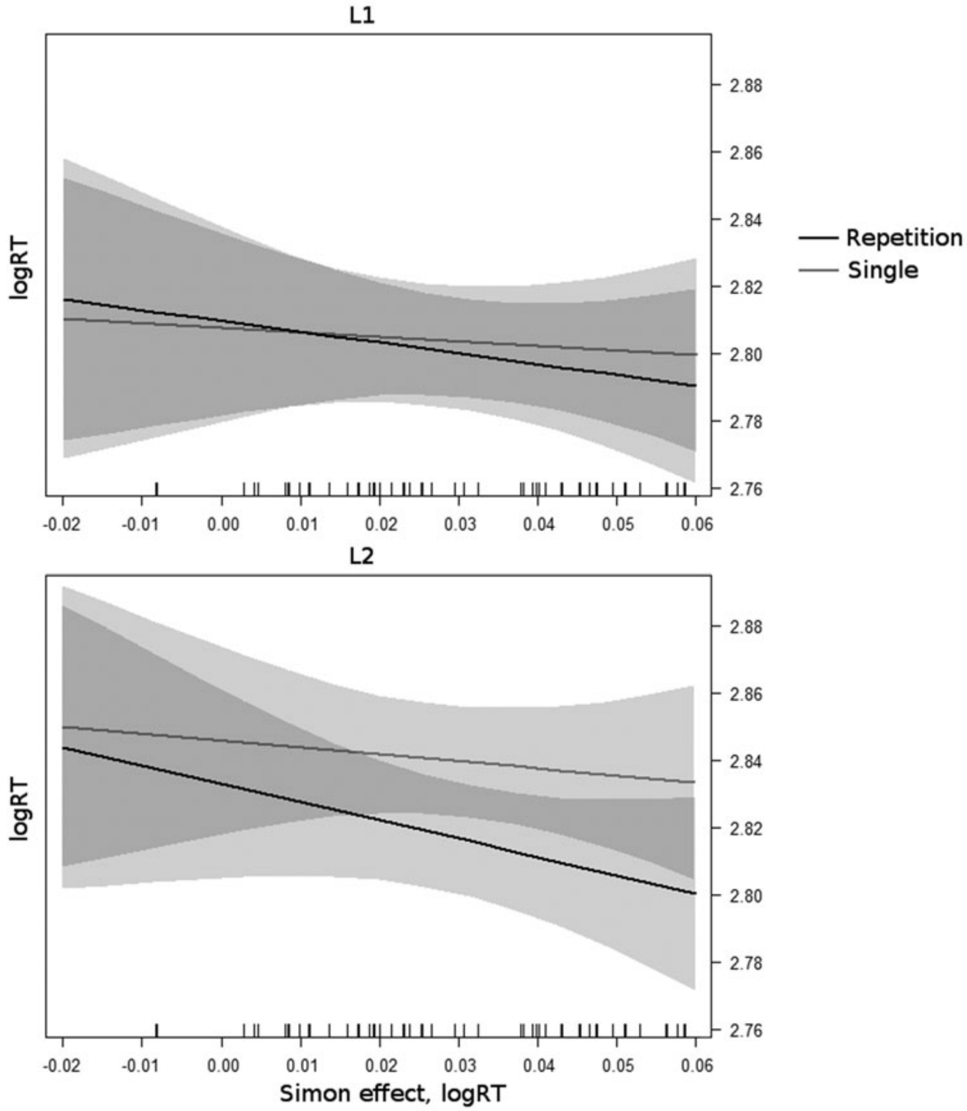

Figure 2. Mixing cost × Simon effect interaction in L1 and L2. Shaded areas represent standard errors.

### *3.2. Mixing and switch costs and the EF measures*

The mediating effects of the four executive task cost measures (Simon, Flanker, NLSE, and NLME) were investigated in models including the log-transformed reaction time as the dependent variable and Language, Condition, and one of the cost measures at a time as predictors. Subject and Stimulus were included as random variables.

#### *The Simon effect*

The Simon effect mediated the mixing cost in both L1 ($E = .19$, $t = 2.28$, $p < .05$) and L2 ($E = .34$, $t = 4.07$, $p < .001$). From Figure 2 we see that in both languages, repetition trial performance correlated more negatively with the Simon effect than the single block performance. In both languages, the mixing cost became more negative the higher the Simon effect. Although this interaction appears to be stronger in L2, the difference (i.e., the Language × Mixing cost × Simon effect interaction) was not statistically significant ($t = 1.28$, $p > .1$). The Simon effect did not predict any of the switch costs ($p$'s $> .1$).

Possible associations between the Simon effect and overall performance in the single vs. mixed blocks was examined in a linear mixed model with logRT as dependent variable; Simon effect, Language, and Block (Mixed or Single) as predictors; and Subject and Stimulus as random variables. The Simon effect did not predict performance in any of the blocks in either language ($p$'s $> .1$).

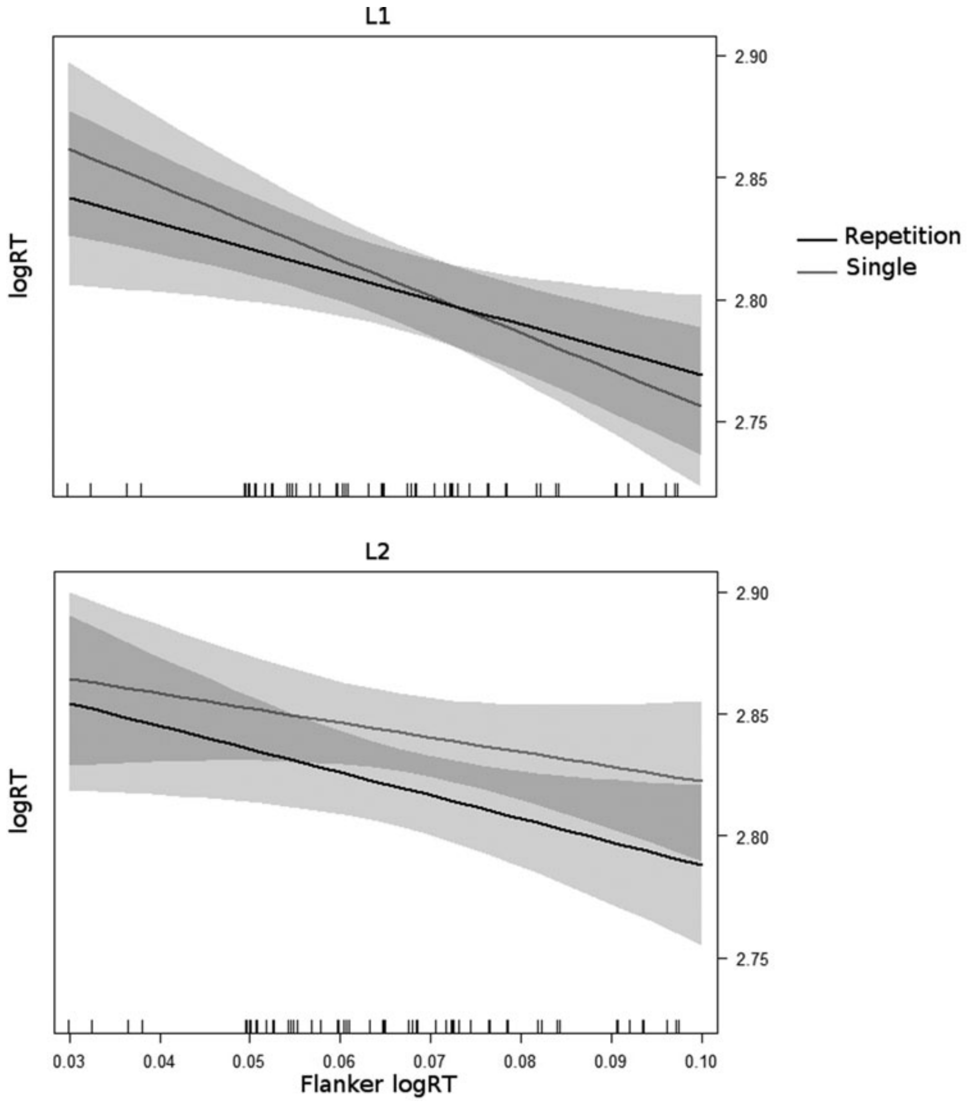

Figure 3. Mixing cost × Flanker effect interaction in L1 and L2. Shaded areas represent standard errors.

### *The Flanker effect*

The Flanker effect predicted the mixing cost in both L1 and L2, but in opposite directions (see Figure 3). In L1, there was a mixing advantage for subjects with a low Flanker effect, but a mixing cost for subjects with a high Flanker effect ($E = -.47$, $t = 5.03$, $p < .001$). In L2, the mixing advantage was stronger the higher the Flanker effect ($E = .35$, $t = 3.71$, $p < .001$). Also the Mixing cost × Flanker × Language interaction was significant ($E = .82$, $t = 6.18$, $p < .001$), indicating that this difference between languages in how the Flanker effect predicted the mixing effect was statistically significant.

Possible associations between the Flanker effect and overall performance in the single vs. mixed blocks was examined in a linear mixed model with logRT as dependent variable; Flanker effect, Language, and Block (Mixed or Single) as predictors; and Subject and Stimulus as random variables. In L1 the Flanker effect correlated negatively with both mixed ($E = -.94$, $|t| = 2.19$, $p < .05$) and single block ($E = -1.48$, $|t| = 3.44$, $p < .01$) performance; that is, in both languages reaction times were faster the higher the Flanker effect. In L2 the Flanker effect correlated negatively with mixed block performance ($E = -.97$, $|t| = 2.25$, $p < .05$) but not with single block performance ($p > .1$).

### *The number-letter task*

The number-letter task was used to examine whether a subject's general set shifting capacity correlated with their language switching and mixing performance. We focused on the relationship between the NLSE and the language switch cost on the one hand, and the NLME and the language mixing cost on the other.The NLSE did not predict the switch costs in either language, or their

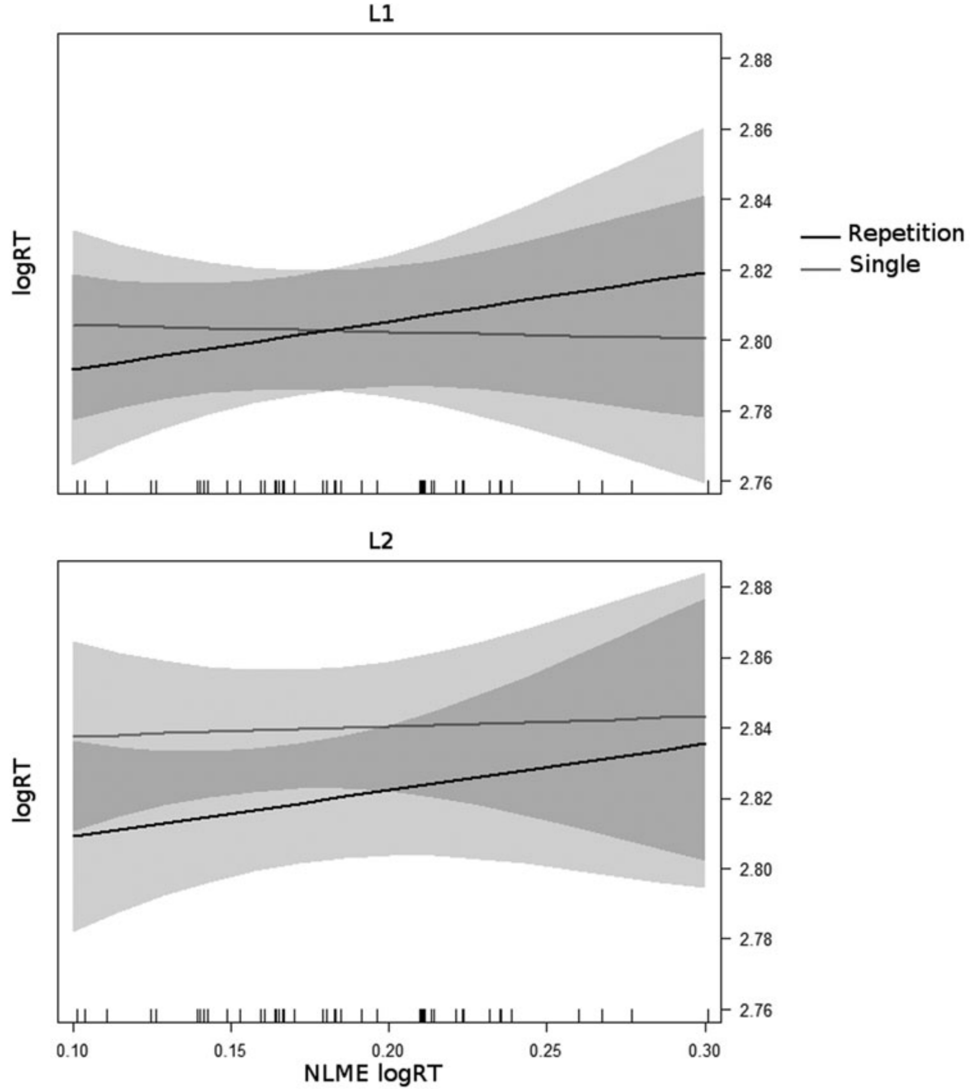

Figure 4. Mixing cost × NLME interaction in L1 and L2. Shaded areas represent standard errors.

asymmetries ($p$'s $> .1$). The NLME predicted the mixing cost in both L1 ($E = -.18$, $t = 6.61$, $p < .001$) and L2 ($E = -.076$, $t = 2.75$, $p < .01$; see Figure 4). In L1, there was a mixing advantage when the NLME was low, but a mixing cost when the NLME was high. In L2, there was a mixing advantage throughout the values of NLME, but it became weaker when the NLME increased.

### 3.3. *Switch and mixing costs and L2 proficiency*

To test whether the switch and mixing effects were mediated by L2 proficiency, a model using log-RT as dependent variable and Condition, Language, and L2 proficiency as predictors was employed. Subject and Stimulus were used as random variables. L2 proficiency mediated the mixing effect in L1 ($E = -.00051$, $t = 3.61$, $p < .001$; see Figure 5) but not in L2 ($p > .1$). In L1, there was a mixing advantage in subjects with low L2 proficiency, but a mixing cost in subjects with high L2 proficiency. Figure 5 shows that L2 proficiency correlated more negatively with L1 single block performance than L1 repetition trial performance.

## 4. Discussion

The present study aimed to examine switch and mixing costs in a language-general semantic categorization task. Earlier studies have found a switch cost in these types of tasks, but the mixing cost has not been examined earlier. Including single language blocks in the setup enables assessing how lexical control processes differ between single and mixed language contexts. We also examined the connections between executive functions and the language switch and mixing costs. Our aim was to see whether

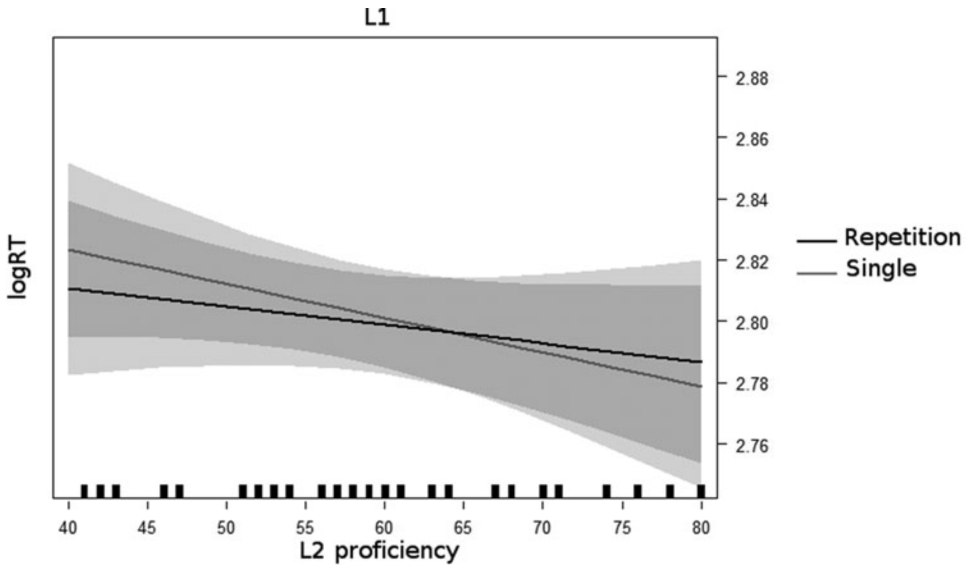

Figure 5. L1 mixing cost × L2 proficiency interaction. Shaded areas represent standard errors.

general inhibition and set shifting capacity play a role in receptive language switching and mixing as they are hypothesized to do in language production.

### *4.1. Language switch and mixing costs*

The current study showed a similar, significant switch cost in both L1 and L2, in line with earlier results (Macizo et al., 2012; von Studnitz & Green, 2002). The switch cost is in line with the BIA model, which takes it to stem from within-lexicon inhibitory connections between the language nodes. The BIA+ model, on the other hand, takes lexical access to be wholly non-selective and arguably implies no switch cost. One could, however, argue that the BIA+ model is compatible with a small switch cost that could be due to language priming. Although lexical access is non-selective, an L1 word activates L1 lexical representations more strongly than L2 lexical representations, and vice versa. This would be because words are orthographically more similar within language than between languages. If we suppose that all words of a language L are to some extent activated during L trials, this would cause a switch cost: on an L switch trial, L has to be activated from the baseline whereas on an L repetition trial, L is already active to some extent. On this account, switch costs should be higher for languages that are orthographically less similar. Language priming implies no switch cost asymmetry: L words activate lexical representations of L based on their orthographic features alone, so the strength of this effect should depend solely on within-language orthographic similarity. The problem with this line of argumentation is that it makes the BIA+ model compatible with both the presence and absence of a switch cost, making the model difficult to falsify.

The switch costs in our study were of symmetrical strength, in line with the results of Macizo et al. (2012) and von Studnitz and Green (2002) (but see Jackson et al., 2004; Pellikka et al., 2015). This is not in line with the IC model, which predicts switch cost asymmetry in unbalanced bilinguals.

There was a strong (36 ms) mixing advantage in L2 but no significant mixing effect in L1. In other words, in L2 the subjects performed better in the repetition trials of the mixed block than in the single block. This finding was strong and could not be accounted for by possible repetition priming in the mixed block. In the light of previous results in language production (see the review by Bobb & Wodniecka, 2013), we would have expected the single block trials to be processed more quickly than the mixed block trials, where language switching would presumably slow down performance.

Green and Abutalebi (2013) put forward an Adaptive Control (AC) hypothesis, which could shed some light on the L2 mixed block advantage. According to the model, the lexical control processes adapt to the interactional context. There are three such contexts: a single language context, where only one language is used; a dual language context, in which different languages are used but typically with different persons; and a dense code-switching context, where any language can be used even within a single discourse. Based on the AC hypothesis, interference control (including inhibition) is central in a single language context, whereas in a dense code switching context *opportunistic planning* can be employed (Green & Abutalebi, 2013). In opportunistic planning, the subject makes use of “whatever comes most readily to hand in order to achieve a goal”. We may re-formulate this as a claim that, in a dense code-switching context, the lexical routes of both languages of a bilingual can be utilized to make a response. Opportunistic planning is, thus, an antipode to interference control, where the non-target language is actively suppressed.

While the single language block can be considered as a single language context, the mixed block can be seen as a dense code-switching context. If the subjects employ opportunistic planning in the mixed block, they may utilize the fastest lexical route to make a semantic categorization. In the single block, on the other hand, interference control is utilized, and the non-target language route is suppressed. The possibility of using the faster L1 route to a decision in the mixed block facilitates processing in L2 trials. In L1 mixed block trials, in contrast, processing is already close to ceiling and little or no advantage is achieved by utilizing the L2 route, which is typically slower.

In more detail, the opportunistic planning hypothesis can be formulated as follows, following the lines of the Revised Hierarchical Model (RHM; Kroll & Stewart, 1994). The RHM focuses on the development of the lexicon and can be applied to the late Finnish-English bilinguals in the current study, as some of our participants were possibly still on the learning curve. A stimulus word in L2 such as “cat” activates the corresponding L2 lexical representation <cat>, which has excitatory connections to the L1 translation equivalent <kissa>. Both lexical representations have excitatory links to the lexical concept CAT, which determines the behavioral response to the stimulus. However, the excitatory links between the translation equivalents are not symmetric in strength: the link from <cat> to <kissa> is stronger than that from <kissa> to <cat>. Likewise, the link from <kissa> to the concept CAT is stronger than from <cat> to CAT (cf. Kroll & Stewart, 1994). Thus, the route from the stimulus word “cat” can be faster to the concept through the corresponding L1 lexical representation <kissa> than through the direct route from <cat>. Hypothetically, this faster route could be opportunistically employed according to the AC hypothesis. In contrast, in the single language block the subject utilizes interference control and the non-target language lexical nodes are suppressed. The facilitation occurs specifically in L2 and not in L1 because in L1, the fastest possible route is already used and only little or no advantage can be achieved through the engagement of the L2 route.

Another way to approach the L2 mixed block advantage is from a purely statistical perspective, applying a *horse race model* (Raab, 1962). In parallel processing two routes are available to make a response. When the reaction time distributions of the two routes overlap, the faster route can be utilized. For instance, if the route through the L1 lexical representation <kissa> happens to be faster than the route through the L2 lexical representation <cat>, then the former route will reach the “goal” in a shorter time, resulting in facilitation. This can take place in the mixed block where both routes are activated, but not in the single block where only one route is active and there is no overlap in the RT distributions (see Figure 6). Note that the horse race model is a purely statistical explanation of the facilitation effect and largely independent of how the facilitation is realized on the cognitive or neural level; the model only assumes parallel processing.

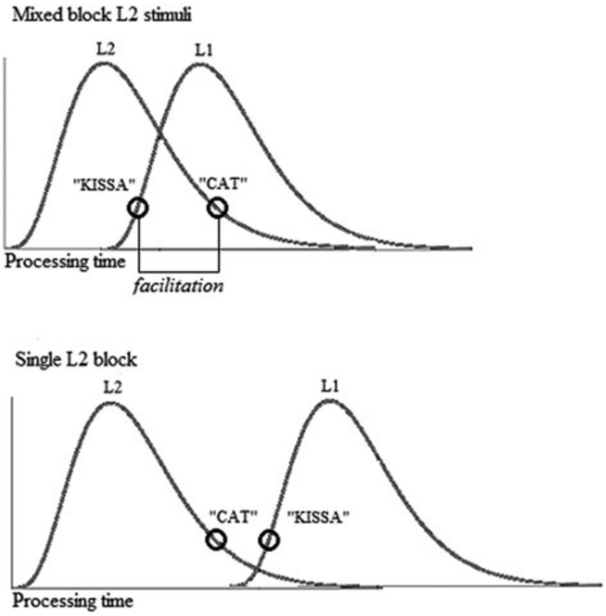

Figure 6. Parallel processing facilitation in a horse race model.

### 4.2. *The mediating effects of the executive tasks*

**_Inhibition_**

We predicted that if receptive language switching engages general inhibition, as the IC model suggest, then the switch and mixing costs would be higher for subjects with worse inhibitory capacity. The results did not support this hypothesis. The Simon effect did not predict the switch cost in either language, but it did mediate the mixing advantage in both languages, with the mixing advantage being larger the higher the Simon effect. In both languages, the Simon effect correlated more negatively with the mixed block repetition trial performance than with the single block performance. The IC model predicts the opposite: higher inhibition should result in increased reaction times in the mixed block and more positive mixing costs.[4]

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[4] Here we presume that on the IC model a higher Simon effect, that is, worse inhibitory capacity, would correlate with slower reaction times

The Flanker effect did not predict the switch cost in either language, in contrast with the predictions of the IC model. However, the Flanker effect predicted the mixing cost in both L1 and L2, albeit in opposite directions: in L1 the mixing cost was more positive the larger the Flanker effect (in line with the IC model), but in L2 the mixing cost was more negative (in contrast to the IC model). In sum, the interactions with the inhibitory tasks were inconsistent and did not support the IC model.

In addition to examining the switch and mixing costs, we conducted post hoc analyses on the main effects of the Simon and Flanker tasks in the mixed and single language blocks to examine the implication of the AC model that interference control is central in single language blocks but not in the mixed block. Accordingly, we expected positive associations between Simon and Flanker effects and single block performance (i.e., those with worse inhibitory capacity would perform worse in the single block). The Simon correlations were not significant, but the Flanker effect correlated negatively with both single and mixed block performance in L1, and with mixed block performance in L2. The results are not in line with the AC model. One possible way to account for this inconsistency in the framework of the AC model would be to claim that inhibition has no central role in either block type. Instead, opportunistic planning can be utilized in the mixed block because there both languages are active, unlike in single blocks where only one language is activated by the context.

In sum, the Simon and Flanker interactions were inconsistent. This could be taken to indicate that domain-general interference control has no consistent role in receptive language switching. Similar inconsistency has been found (using approaches different from ours) in earlier studies (Jackson et al., 2004; Pellikka et al., 2015). The inconsistency could also be partly due to the lack of convergent validity of inhibitory tasks, which did not correlate in the present sample ($r = .057, p > .1$). The lack of convergent validity of executive tasks commonly used in bilingualism studies is also noted by Paap and Sawi (2014). It is possible that the Simon and Flanker tasks measure different aspects of inhibition, or that either one or both of them fail to tap into general inhibition altogether (assuming that general inhibition exists).

### *Set shifting*

The number-letter task was used to assess the suggestion of Meuter and Allport (1999) that language switching engages general set shifting processes. The NLSE did not correlate with the language switch costs. This is probably due to the fact that, unlike the number-letter task which employed two task schemas (one response type for a number stimulus and another for a letter stimulus), the semantic categorization task employed only one task schema (one response type for both languages). More generally, the lack of relationship between the NLSE and the language switch cost indicates that a subject's general set shifting capacity is not central in this type of language switching task.

The NLME did, however, predict the language mixing cost in both languages. In both languages, better general monitoring capacity (indicated by a lower NLME) correlated with better language mixing capacity (lower language mixing cost). In line with this, Figure 4 shows that better monitoring capacity correlated with faster reaction times particularly in the mixed block where monitoring is arguably more central than in the single block. However, it is worth noting that the L2 mixing cost was still negative irrespective of the NLME; it was just less negative the higher the NLME. In terms of the AC model, this could suggest that subjects with better monitoring capacity relied more on opportunistic planning. One could speculate that monitoring capacity is central in determining which lexical route leads to the fastest response in the mixed block.

### *Summary of the EF interactions*

To briefly sum up the findings on the associations between general EF and language switching and mixing, the present results are against the IC model as we saw no consistent role for interference control in receptive language switching or mixing. The findings are largely in line with the BIA and BIA+ models, which hold that lexical access in reception operates within the lexicon. It is important to bear in mind that the IC model was originally formulated for language production, where endogenous control is arguably more central than in reception (Peeters et al., 2014; Linck et al., 2012; but see Jylkkä et al., in press). The results do, however, indicate that better general monitoring capacity was related to better language mixing performance. This can be taken to suggest that subjects with better monitoring capacity are better able to keep track of the activation levels of languages in a mixed language context and thus show smaller interference effects from the non-target language. (For similar results in the production domain, see e.g., Jylkkä et al., in press; Prior & Gollan, 2011).

## 4.3. *The mediating effect of L2 proficiency*

Finally, we examined the connections between a subject's proficiency in L2 and the language switch and mixing costs. The only significant effect was related to the L1 mixing cost, which was more positive the higher the L2 proficiency. The correlation between L2 proficiency and reaction times was more negative in the single block than in the repetition trials (see Figure 5). It appears as though

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in the mixed block. This would be because worse inhibitors are less efficient in engaging and resolving non-target language inhibition (cf. Linck et al., 2012).

high proficiency in L2 interfered with L1 processing more in the single block than in the mixed block. This can be interpreted along the lines of the AC model. In the mixed block, opportunistic planning is utilized and no between-language conflict arises, as the lexical routes of both languages can be utilized. In contrast, in the single block interference control is utilized and the non-target language is suppressed. The higher the proficiency in L2, the more difficult it is to suppress it.

### *4.4. Re-evaluation of the theoretical models*

A key problem in interpreting the present results is how switch costs and the hypothesized between-language facilitation are compatible. The switch costs seem to indicate that the non-target language is inhibited (possibly at the lexical level, as suggested by the BIA model), whereas between-language facilitation appears to indicate that lexical selection is non-selective. Supposing that the L2 mixing advantage is in fact due to between-language facilitation, we have to infer that the switch costs must stem from something else than non-target language inhibition. One could argue that the switch cost is due to a simple language priming effect: an L stimulus activates the corresponding lexical concept and to some extent also other lexical representations of L, due to their shared orthographic features. On this account, L trials globally activate the lexical representations of L, causing a repetition trial benefit. However, the lexical representations of the other language L* are not inhibited, and can be utilized if that route is faster.

In sum, the basic switching and mixing results are best in line with the AC model. The interactions with the executive cost effects, in turn, have less clear implications. There was no evidence that inhibition would be central in the single blocks, as implied by the AC model. This can be interpreted as indicating that in reception lexical access is non-selective in the single language blocks as well as mixed language contexts.[5] It could be argued that in the single language blocks, non-selective access does not lead to facilitation as the non-target language is not activated by the context.

## 5. Conclusions

In the present study, we assessed the switch and mixing costs in a language general semantic categorization task and their link to general executive functions. Our goal was to see whether general executive functions, particularly inhibition, are engaged in receptive language switching as they are assumed to be in language production. The results indicated that inhibition does not underlie the language switch and mixing costs, and support the hypothesis that lexical selection in language reception is non-selective. On the other hand, we found some evidence that subjects with better general monitoring capacity are also better language mixers.

Our main novel finding was related to the mixing cost, which has not been investigated in language reception earlier. Whereas in production language mixing typically causes a processing cost, in our receptive task we found that language mixing facilitated responses in the weaker language. We argued that this mixing advantage is due to the use of opportunistic planning in a mixed language context, where response can be made using the fastest available language route, as suggested by the AC model. The phenomenon can also be explained by a purely statistical horse race model, where facilitation occurs when the reaction time distributions of two parallel processing routes overlap.

## Supplementary material

For supplementary material accompanying this paper, visit https://doi.org/10.1017/S1366728917000384

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[5] Note that the AC model was first proposed as a model of language production, where interference control may be more central due to the endogenous nature of the word production process. In reception, the process is arguably more bottom-up driven, lessening the need for endogenous control.

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