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What's Easier: Doing What You Want, or Being Told What to Do? Cued versus Voluntary Language and Task Switching

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Abstract

The current study contrasted cued versus voluntary switching to investigate switching efficiency and possible sharing of control mechanisms across linguistic and non-linguistic domains. Bilinguals switched between naming pictures in Spanish versus English or between reading numbers aloud versus adding their digits, either without or with repetition of stimuli, and with fewer requirements as to when and how much they had to switch relative to previous instantiations of voluntary switching. Without repetition (Experiment 1), voluntary responses were faster than cued responses on both stay and switch trials (especially in the non-linguistic switching task), whereas in previous studies the voluntary advantage was restricted to switch-cost reduction. Similarly, when targets were presented repeatedly (Experiment 2), voluntary responses were faster overall for both linguistic and non-linguistic switching, though here the advantage tended to be larger on switch trials. Experiment 3 confirmed the overall voluntary speed advantage for the read-add task in monolinguals, and revealed a reduction in switch costs only for a different non-linguistic task (size-parity judgments). These results reveal greater overall advantages for voluntary over cued switching than previously reported, but also that the precise manifestation of the voluntary advantage can vary with different tasks. In the linguistic domain, lexical inaccessibility introduces some unique control mechanisms, and repetition may magnify cross-domain overlap in control mechanisms. Finally, under some limited conditions, cost-free switches were found in both linguistic and non-linguistic domains; however, suspension of top-down control may be restricted to language or highly automatic tasks.

Bilinguals switch languages. It is a fundamental part of what it means to be bilingual; if you never switch languages, you are only using one language. Some language switches are required (e.g., when you pick up the phone you might switch to the language dominant in the culture when you say “Hello?”). However, in some contexts, bilinguals switch languages frequently, even though nothing seems to compel them to do so, and even though carefully controlled experimental studies reveal that language switching incurs a significant cost in time. It is possible that bilinguals switch primarily for sociolinguistic reasons that trump any processing costs (which can be measured only in terms of milliseconds). But the question of

why they switch remains relatively unexplored in experimental research even though it seems likely to provide insights about how bilinguals maintain control over language selection. More broadly, bilinguals provide a unique angle from which to view the cognitive mechanisms underlying switching behaviors outside the linguistic domain. What sorts of factors lead to more or less efficient switches, how do linguistic and non-linguistic switches compare, to what extent might cognitive control mechanisms be shared across linguistic and non-linguistic domains, and what do the answers to all of these questions reveal about how switches are initiated in general?

That switches take time to execute might not seem surprising when switches are required. For example, in cued switching paradigms, bilinguals are instructed to name pictures in one language when they see one experimentally provided cue (e.g., a blue background), and to switch languages when a different cue appears (e.g., a red background). *Cued switch costs* reflect the fact that naming responses are significantly slower on switch trials than on stay (non-switch) trials (e.g., Meuter & Allport, 1999). Such cuing procedures lead bilinguals to switch languages even though they normally would not have switched, and there may be important differences between spontaneously occurring versus forced switches. To test this hypothesis, it would be necessary to directly compare cued to voluntary language switches. This specific comparison has not yet been investigated in the domain of language switching, although it has been established that significant switch costs are found even when participants decide for themselves whether to switch or not on a trial-by-trial basis. Such *voluntary switch costs* have been reported both for non-linguistic switching (e.g., switching from judging single digits as even or odd, to judging if they are larger or smaller than 5; Arrington & Logan, 2004), and for language switching (in which bilinguals named some pictures in English and others in Spanish using “whatever language comes to mind”; Gollan & Ferreira, 2009).

In a series of tightly woven experiments using a non-linguistic task switching paradigm, Arrington and Logan (2005) demonstrated that voluntary switching elicits significantly smaller switch costs than cued switching. However, the voluntary over cued advantage was quite limited in nature. For example, in one experiment (most analogous to the experiments reported below), voluntary switches were not faster than cued switches. Instead, voluntary switch costs were smaller than cued switch costs only because cued non-switch responses were faster than voluntary non-switch responses (see Arrington & Logan, 2005, Figure 2). These data demonstrate trade-offs between top-down and bottom-up control processes in switching. Voluntary switching requires deciding whether to stay or to switch (ultimately a process that must be executed top-down¹), and such decisions may be as costly as processing a cue and planning a cued switch. Cued stay responses might be faster than voluntary stay responses because the cue eliminates the need to decide whether to stay or to switch, and cue processing might be easier than making a stay-or-switch decision. In a subsequent experiment, the switch responses themselves were faster when voluntary than

¹Following Arrington & Logan (2005), we use the term *top-down* to refer to cognitive processes that support and elicit volitional control (endogenous executive processes that actively configure and prepare the cognitive system to perform a given task), and *bottom-up* to refer to processes that are triggered automatically by the stimulus and therefore would inherently be non-voluntary (via passive interactions with a successive task).

when cued (see Arrington & Logan, 2005, Figure 3). However, in this experiment, cued switches might have been slowed (inferred here by comparing Figures 2 and 3 of Arrington & Logan, 2005) by the inclusion of multiple cues for each task to differentiate cue repetition from task repetition.

An important consideration that could have masked the extent to which voluntary switching might be easier than cued switching is that switching was not fully voluntary. Indeed, in the majority of studies on voluntary switching, participants were required to perform each task about 50% of the time, and to attempt to execute each task more or less randomly. It is possible that removing these requirements would paint a different picture regarding the relative trade-off between top-down and bottom-up processes in switch costs (perhaps revealing voluntary switching to be more clearly easier than cued switching). Additionally, the finding that switch costs varied in size in systematic ways depending on processing requirements across tasks opens up the possibility that switches might be less costly, or perhaps even not costly at all, in some as-yet unidentified set of experimental or naturally occurring conditions. For example, switches back into highly automatic tasks (e.g., reading) might be driven by bottom-up association between a stimulus and a response, or, for bilinguals, some objects might activate a name in one language much more than in the other language. The observation of significant voluntary language switch costs might seem inconsistent with this proposal (Gollan & Ferreira, 2009). However, significant switch costs averaged across trials does not require all switches to be costly. If bilinguals decided to switch despite the costs on a subset of trials, this would produce switch costs when averaging across trials that would mask the absence of switch costs on other trials (on which switches were triggered more automatically).

Direct comparisons between published studies, either within the linguistic domain (i.e., of cued versus voluntary language switching) or across domains (language switching versus non-linguistic switching), are difficult because of at least four methodological differences between studies. First, most language switching studies included a restricted set of stimuli (digits 1–9) that were presented repeatedly (e.g., Meuter & Allport, 1999), whereas in the one published study of voluntary language switching, bilinguals named each of 132 pictures only once (Gollan & Ferreira, 2009). Second, in studies of voluntary non-linguistic switching the two response alternatives for any given stimulus were always readily accessible, whereas bilinguals in Gollan and Ferreira's study did not know all of the picture names in both of their languages (some relatively more difficult-to-name pictures were included to avoid repetition of items).

Third, response modality differs across domains: Language switching entails voice responses, whereas participants in the non-linguistic switching studies responded with button presses, which require learning arbitrary button-response mappings. Finally, as noted above, language switching study participants could use whichever language came to mind on each trial without restrictions, whereas the non-linguistic task switching studies required participants to perform each task about 50% of the time and to respond randomly. These requirements greatly reduce the extent to which switches can be characterized as voluntary, and could induce strategies that do not reflect processes involved when switches occur in more natural settings. Consistent with this hypothesis, bilinguals in Experiment 2 of Gollan

and Ferreira (2009) were instructed to use each language about 50% of the time, and this produced switch facilitation effects instead of switch costs – that is, responses were *faster* on switch than on non-switch trials. This demonstrated that seemingly small changes in task instructions can have powerful effects on the type of voluntary costs that are observed, and also that there may be important differences between language switching and non-linguistic switching.

Aims of the Current Study

In the current study, we aimed to bridge some of the gaps between the literatures on linguistic and non-linguistic task switching, and between cued and voluntary language switching, by addressing several outstanding questions. In particular, we aimed to investigate more fully voluntary switching, whether language switching might reveal cost-free switches, and to evaluate proposals that bilinguals rely on executive control to achieve language control (e.g., Bialystok, Craik, Green, & Gollan, 2009) by comparing language switching and non-linguistic switching when controlling as much as possible for methodological differences across domains.

We hypothesized that unique control mechanisms might emerge in the domain of language control, and that engagement of inhibitory control might be more likely in linguistic than in non-linguistic switching. Often viewed as the hallmark of inhibitory control, switch costs are sometimes larger when switching into a dominant language or an easier task than when switching into the non-dominant language or a more difficult task – an effect known as the *switch cost asymmetry* (e.g., Allport, Styles, & Hsieh, 1994; Meuter & Allport, 1999; for review see Koch, Gade, Schuch, & Philipp, 2010). On this view, when bilinguals want to speak the non-dominant language, they inhibit the dominant language and subsequently have to release inhibition to go back to the dominant language (Green, 1986; 1998; Meuter & Allport, 1999). This interpretation of switch cost asymmetries has been challenged (both within and outside the literature on language switching; Finkbeiner, Almeida, Janssen, & Caramazza, 2006; Runnqvist, Strijkers, Alario, Costa, 2012; Verhoeef, Roelofs, & Chwilla, 2009; Yeung & Monsell, 2003; but see Peeters, Runnqvist, Bertrand, & Grainger, 2014). However, we suggested (Gollan & Ferreira, 2009) that even stronger evidence for inhibition of the dominant language comes from the elimination of, or sometimes even full reversal of, language dominance effects in mixed-language blocks (e.g., Christoffels, Firk, & Schiller, 2007; Costa & Santesteban, 2004; Verhoeef et al., 2009). In the current study, we included a non-linguistic switching task (reading numbers aloud vs. adding their digits) with a clearly dominant response (reading), to consider the possible role of inhibition across cued and voluntary, and linguistic and non-linguistic, switching tasks, as reflected by potentially asymmetric switch costs and eliminated or reversed dominance effects in one or both domains.

Additionally, we investigated more fully voluntary switching instructions, and switch costs *without* repetition of stimuli in the non-linguistic domain and *with* repetition in the linguistic domain, as both of these conditions are unexplored in the existing literature. We hypothesized that greater similarities might be observed across linguistic and non-linguistic domains with repetition of materials, in part because repetition would reduce inherent

differences between domains related to language dominance effects. Repetition could also alter the extent to which switches are driven by bottom-up versus top-down processes. In particular, we hypothesized that with repetition, bilinguals might be able to allow lexical accessibility to drive switching based on associations between each picture and one language, revealing cost-free voluntary switches controlled by bottom-up automatic activation (a question explored in detail in Experiment 2).

To facilitate interpretation relative to the existing literature on voluntary switching, we compared cued and voluntary switching both without repetition (in Experiment 1) and with repetition (in Experiment 2). In both experiments, we also compared language switching to a non-linguistic switching task in which participants saw two- to four-digit numbers (e.g., 22) and alternated between reading them aloud (“twenty-two”) versus adding their digits (“four”). We developed the latter task to be as analogous as possible to language switching by eliciting vocal responses, likely showing clear dominance effects, and using stimuli that made it possible to avoid repeating items (by offering a broad range of possible materials). Finally, to consider the generalizability of the present findings, we compared the new non-linguistic switching task to a commonly used non-linguistic switching task in monolingual participants (in Experiment 3). Differences between Experiments 1–3 and the details of each task are shown in Table 1.

Experiment 1: Cued versus Voluntary Switching Without Repetition of Stimuli

We began by asking a very specific question about voluntary language switching. In previous work (Gollan & Ferreira, 2009), both the dominant and the non-dominant languages exhibited significant voluntary switch costs (which contrast stay with switch trials in the mixed-language block). However, a different pattern was observed for mixing costs, which contrast non-switch trials in the mixed-language block with non-switch trials in single-language blocks in which pictures were named only in Spanish or only in English. Only the dominant language exhibited a voluntary mixing cost, such that bilinguals responded more slowly in the mixed-language block than in the single-language block. In contrast, in the non-dominant language there was an effect in the opposite direction, i.e., a mixing facilitation effect, such that bilinguals responded more *quickly* in the mixed-language block than in the single-language block. This pattern of results was highly unusual, as studies of cued language switching generally show mixing costs for both the dominant and the non-dominant languages (e.g., Christoffels et al., 2007). Gollan and Ferreira (2009) hypothesized that in the voluntary mixed block, bilinguals switched into the non-dominant language only to name relatively easier pictures and then bailed back into the dominant language to name more difficult pictures. Thus, although the dominant language appeared to exhibit a robust voluntary mixing cost, it is not clear if language mixing might nevertheless be more efficient overall when voluntary than when cued (when averaging across the two languages in the mixed-language blocks).

Experiment 1 addressed this question by directly comparing voluntary and cued language switching using a procedure that closely matched that reported by Gollan and Ferreira (2009). Averaged across languages, responses should be faster overall in the voluntary than in the cued block if language switches can be driven primarily by bottom-up cues (i.e.,

lexical accessibility of names in each language), and if all or most bilinguals tested allow switches to be fully controlled in this fashion. Based on previous work on non-linguistic switching (Arrington & Logan, 2005), we expected to find smaller switch costs in voluntary than in cued language switching, a result that would imply overlapping processing mechanisms underlying linguistic and non-linguistic switching.

Methods

Participants—Ninety-six Spanish-English bilinguals from UCSD participated for course credit. Twenty-seven of these (or 28% of bilinguals tested) did not switch languages enough in the voluntary language block to produce data in the four conditions of interest (i.e., stay and switch trials in the dominant and non-dominant languages), and one more had only a single switch trial in each language. Due to the importance of making the contrast between cued and voluntary blocks a within-subjects comparison, these 28 bilinguals were excluded from the picture naming analyses. Ten bilinguals (or 10% of bilinguals tested) did not switch tasks enough in the voluntary non-linguistic task block to produce data in the four conditions of interest (i.e., stay and switch trials in the read and add tasks) and were excluded from the read-add analyses. Following these exclusions, 62 bilinguals contributed data to both analyses, 6 bilinguals contributed data only to the picture naming analysis, and 24 bilinguals contributed data only to the read-add analysis.

Table 2a illustrates the characteristics of participants who were included and excluded from statistical analyses. All bilinguals reported learning to speak Spanish before English at home. Seventy-nine reported being English-dominant or balanced; for these bilinguals, English responses were classified as dominant and Spanish as non-dominant. These dominance classifications were reversed for the remaining bilinguals, who reported being Spanish-dominant ($n=17$, of whom 14 were included in the picture naming task analyses). Self-reported proficiency is strongly correlated with objective measures of proficiency (Marian, Blumenfeld, & Kaushanskaya, 2007), and bilinguals are better at self-reporting language dominance than they are at reporting absolute proficiency level (Gollan, Weissberger, Runnqvist, Montoya, & Cera, 2012).

Materials and procedure—Bilinguals completed a language history questionnaire and then were tested on the language switching task and the read-add task, in counterbalanced order. Within each task, both non-mixed blocks were always administered first (i.e., single-language conditions (English or Spanish) and single-task conditions (read or add)), followed by both switching conditions (cued and voluntary switching), in counterbalanced order. Thus, the order of domain (linguistic, non-linguistic), and the order of mixed blocks within each task (cued, voluntary), were counterbalanced between participants, but participants always completed two non-mixed blocks before completing two mixed blocks within each domain.

Language task: Target picture naming stimuli included 192 black-and-white line drawings of pictures. English names, which varied widely in frequency, averaged 61 per million ($SD=105$; median=21) in CELEX frequency (ESL dictionary; Baayen, Piepenbrock, & van Rijn, 1993), and were on average 1.5 syllables in English ($SD=0.6$; range 1–4) and 2.6

syllables in Spanish ($SD=0.8$; range 1–5). We did not exclude cognates entirely; however, only 16 (8.3%) of the items were cognates. Items were rotated in groups across conditions so that each bilingual saw each picture only once, and named 32 pictures in an English-only condition, 32 in a Spanish-only condition, 64 in a cued switching condition (32 in each language), and 64 in a voluntary switching condition (in which bilinguals decided for themselves how many pictures to name in each language). Half of the pictures in every block, and in every condition of the cued switching block, had low-frequency names as determined by a median split ($M=9$; $SD=6$) and the other half had high-frequency names ($M=114$; $SD=129$). Each condition began with 9 practice trials of digit naming to familiarize participants with the task demands. After a break in which participants were informed that they would begin picture naming, 4 practice trials (one of which was a switch trial in the cued-switch condition) were followed without break or warning by the experimental trials. Practice pictures also served to set the task for the first trial of the cued block (i.e., as a stay or a switch trial).

In the cued-switch picture naming block, language switches were cued on 8 of the 32 pictures named in each language; this 25% switch rate matches the average switch rate reported for voluntary switching in Gollan and Ferreira (2009), and was achieved by creating 24 lists with 24 different pseudo-random orders which limited the number of pictures that could be named in each language on successive trials to 6 and the number of consecutive switch trials to 2. Across each group of 24 participants, each item appeared 4 times in the English-only block, 4 times in the Spanish-only block, 8 times in the voluntary switching block, and 8 times in the cued switching block. Within the cued switching block, each item appeared 3 times in English-stay trials, 3 times in Spanish-stay trials, 1 time in an English-switch trial, and 1 time in a Spanish-switch trial.

An experimenter recorded naming and voice-key accuracy online and later verified coding against the recordings. Bilinguals were instructed in English to name pictures in English in the English-only condition, and to name them in Spanish in the Spanish-only condition. In the cued switch condition, bilinguals were instructed to name pictures in English when they saw the USA flag, and in Spanish when they saw the Mexican flag. In the voluntary switch condition, both flags (cues) appeared on the screen and bilinguals were told to “Name each picture using whichever language comes to mind first.”

Non-linguistic task: Target read-add stimuli included 192 two-, three- and four-digit numbers. To make the task as comparable as possible to the picture naming task, we attempted to include numbers that ranged in difficulty, with about half ‘easy’ and half ‘difficult.’ Two-, three-, and four-digit numbers were classified as ‘easy’ if they contained repeating digits (e.g., 44, 505, 2010) or at most one digit greater than 1 (e.g., 40, 201, 5100; note that all numbers in Experiments 1 and 2 were presented without commas). Furthermore, every easy three-digit number had at least one 0 and every easy four-digit number had at least two 0s. Two-digit numbers were classified as ‘difficult’ if they contained two non-repeating digits greater than 1 (e.g., 29, 74). Three- and four-digit numbers were classified as difficult but not too difficult to be included if they contained repeating digits less than 5 (e.g., 331, 441, 1440) or at most one digit greater than 5 (e.g., 112, 251, 731). Furthermore, every difficult three-digit number had at least one 1, and every difficult four-digit number

had at least one 0 and one 1. Three and four-digit numbers that contained a 7 or higher did not contain another number greater than 3. Numbers never had more than one digit greater than 5 unless they included only repeating numbers (e.g., 66).

Read-add stimuli were rotated in groups across conditions so that each participant saw each number only once (with the exception of the number 1100 which was presented twice to each participant by mistake). As in the picture naming task, each participant was presented with 32 numbers in a read-only condition, 32 in an add-only condition, 64 in a cued-switching condition (32 in each task), and 64 in a voluntary-switching condition (in which participants decided for themselves which items to read or add). Half of the numbers in every block, and in every condition of the cued switching block, were easy and the other half were difficult. Each condition began with 16 practice trials (using different numbers than in the experiment) to familiarize participants with task demands. In all other respects, the structure of trials and blocks, the cued switching rate, and the counterbalancing were the same as for the picture naming task.

Bilinguals were instructed to “Read aloud the number formed by the digits” in the read-only condition, and to “Add the digits and say their sum out loud” in the add-only condition. In the cued switch condition, bilinguals were instructed to read the number when they saw a picture of a book, and to add the digits when they saw a picture of a calculator. In the voluntary switch condition, both pictures (cues) appeared on the screen and bilinguals were told to “Perform whichever task comes to mind first.” All bilinguals completed both read and add tasks in English only.

Trial structure: Stimuli were presented using PsyScope X software (Build 51; Cohen, MacWhinney, Flatt, & Provost, 1993; <http://psy.ck.sissa.it>) on an iMac 7 computer with a 20-inch color monitor. Each trial started with a fixation cross presented for 350 ms, followed by a 150 ms blank screen. The language cue or task cue then appeared on the screen for 250 ms, 5.4 cm from the center of the cue above the center of the fixation cross. The cue remained on the screen, and the target appeared in the center of the screen. The cue and target remained on the screen until the participant responded, or for a maximum duration of 3 seconds. An 850 ms inter-trial blank screen interval was presented before the onset of the following trial.

Analysis: Two sets of analyses were conducted using mixed-effects models (Baayen, Davidson, & Bates, 2008). The first analysis establishes the presence of significant dominance effects in single-language and single-task blocks by comparing dominant responses to non-dominant responses for both the picture naming and read-add tasks. The factors for this analysis were domain (linguistic (picture naming), non-linguistic (read-add)), dominance (dominant, non-dominant), and their interaction. The second analysis compared cued to voluntary mixed blocks. The factors for this analysis were domain (linguistic, non-linguistic), dominance (dominant, non-dominant), trial type (stay, switch), instruction type (cued, voluntary), and their interactions. For each analysis, models were also fit separately to the data from the picture naming and read-add tasks to evaluate effects separately for each domain. The results of these analyses are fully reported in tables; when referenced in the text, only *t* values are (re-)reported to convey the robustness of individual effects.

In addition to the by-domain and cross-domain models, planned contrasts and post hoc analyses were conducted to explore effects within certain conditions. Every such analysis included all possible main effects and interactions as fixed effects. (So, for example, an analysis to determine whether the effect of instruction type was significant for dominant-language trials would include instruction type, trial type, and their interaction.) Effects reported from these analyses include estimates, standard errors, and *t* values.

Participants and items (pictures and numbers) were treated as random factors. All fixed effects were allowed to vary by all random factors in all analyses (Barr, Levy, Scheepers, & Tily, 2013), with two exceptions in the cross-domain analysis: First, effects of domain were not allowed to vary by items (because domain is a between-items factor); second, due to convergence issues, the three-way interaction between domain, trial type, and instruction type, as well as the four-way interaction, were not allowed to vary by participants. (These random slopes were dropped because exploratory analyses revealed that neither of their corresponding fixed effects approached significance.)

In accordance with common practice for large psycholinguistic data sets analyzed with mixed-effects models, *t* values are treated as *z* values for the purposes of determining statistical significance (cf. Baayen, 2008). As such, absolute *t* values greater than or equal to 1.96 are taken to be significant; absolute *t* values greater than or equal to 1.65 but less than 1.96 are taken to be marginally significant. All predictors were centered.

Results—The 92 participants who switched into and stayed in each language or each task at least once provided data for 29,568 trials, of which 87.8% (25,951) were analyzed. Trials were excluded when a participant produced a response that did not match the target name or an acceptable alternative (1,666 picture naming trials, 902 read-add trials), when the experimenter determined that the recorded reaction time was invalid (due to, e.g., coughing or overt hesitations; 594 picture naming trials, 144 read-add trials), or when a participant responded faster than 250 ms (10 picture naming trials, 17 read-add trials) or did not respond within 3000 ms (393 picture naming trials, 214 read-add trials). (Note that some trials violated multiple criteria.) When trial type was undefined in the voluntary switching block (e.g., because the preceding trial was excluded due to an omission), it was determined relative to the language used on the most recent trial on which the participant gave a response. The models are summarized in Tables 3 and 4, and results are shown in Figure 1a and 1b. (Data from participants who were excluded from analysis are discussed in Appendix A. We do not report detailed statistical analyses of error rates; however, because errors could affect interpretation of RTs, they are discussed in Appendix B, and possible speed-accuracy tradeoffs are noted below.)

Choices to switch: In the voluntary condition, included and excluded bilinguals collectively switched on 28% of picture naming trials (*SD*=17%) and 32% of read-add trials (*SD*=15%), thereby closely matching the switch rate in the cued condition. However, among the participants who were included in the analyses below, bilinguals switched on 37% of picture naming trials (*SD*=11%) and 36% of read-add trials (*SD*=12%), which is higher than the switch rate in the cued condition.

Dominance without mixing: When naming pictures in the single-language conditions, bilinguals responded faster in their self-reported dominant than non-dominant languages, $t = 9.01$. Analogously, in the single-task conditions, bilinguals responded faster when reading than when adding numbers, $t = 15.42$. Relative to the picture naming task, RTs were faster and dominance effects were larger for the read-add task, as indicated by a main effect of domain, $t = -7.97$, and an interaction between domain and dominance, $t = 4.84$, respectively.

Language mixing: Cued versus voluntary: To briefly summarize the results of greatest interest: There was a voluntary advantage for non-dominant responses but not for dominant responses. Results in the cued condition alone replicated findings reported previously for cued language switching, including both faster responses and greater switch costs in the dominant language than the non-dominant language. Additionally, the switch cost asymmetry was less robust in the voluntary condition than in the cued condition, and language dominance effects were eliminated in the voluntary condition (numerically reversed, even).

In the mixed-language blocks, bilinguals named pictures more quickly in the dominant language, as indicated by a main effect of dominance, $t = 3.49$. However, the dominance effect was only evident in the cued condition, $\beta = 127.2$, $SE = 19.4$, $t = 6.57$, and not in the voluntary condition, where it was marginally significant in the opposite direction, $\beta = -33.3$, $SE = 19.1$, $t = -1.74$. This replicates prior work and reflects bilinguals' choice to name only very easy pictures in the non-dominant language in the voluntary switch condition (for which the dominance effect reversed; see Figure 1a; see also Gollan & Ferreira, 2009). Switch costs were significant overall, as indicated by a main effect of trial type, $t = 9.05$, and were significant in both the cued condition, $\beta = 109.4$, $SE = 16.7$, $t = 6.57$, and the voluntary condition, $\beta = 89.5$, $SE = 16.1$, $t = 5.54$. Overall, there was no difference in RTs between the voluntary and cued conditions, as indicated by a non-significant effect of instruction type, $t < 1$.

As shown in Figure 1a, there were a number of significant interactions, but not in the expected directions based on previously reported comparisons of cued to voluntary switching. For switching between non-linguistic tasks, Arrington and Logan (2005) reported that voluntary switches were executed at the same speed as or more quickly than cued switches, but non-switch trials exhibited the opposite pattern (cued-stay responses were faster than voluntary-stay responses, a condition by trial type interaction). No such interaction between instruction type and trial type was observed in the picture naming RTs, $t = -1.26$. In addition, while responses in the non-dominant language were faster in voluntary than in cued switching (collapsed across stay and switch trials), $\beta = -88.1$, $SE = 17.4$, $t = -5.07$, dominant language responses exhibited the opposite pattern (i.e., were faster in cued than in voluntary switching), $\beta = 54.8$, $SE = 19.0$, $t = 2.88$. This interaction between language dominance and instruction type was significant, $t = -6.03$.

Finally, there was also a switch cost asymmetry (e.g., Meuter & Allport, 1999), such that switch costs were larger in the dominant than in the non-dominant language, as indicated by an interaction between dominance and trial type, $t = -3.08$. This asymmetry was more robust for the cued condition, for which switch costs were significantly larger for the

dominant than for the non-dominant language, $\beta = -95.1$, $SE = 33.8$, $t = -2.82$, than for the voluntary condition, for which the asymmetry was only marginally significant, $\beta = -53.5$, $SE = 29.1$, $t = -1.84$. This demonstration of a more robust switch cost asymmetry for bilinguals in the cued condition agrees with our previous suggestion (Gollan & Ferreira, 2009) that the voluntary instruction allows unbalanced bilinguals to function more like balanced bilinguals in a mixed-language block, reducing switch cost asymmetries and eliciting reversal of language dominance effects in the mixed-language block (Costa & Santesteban, 2004).

The three-way interaction was not significant, $t < 1$.

Task mixing: Cued versus voluntary: Summarizing key results: In the mixed-task blocks, significant switch costs were found in both cued and voluntary conditions. Voluntary responses were faster than cued for both tasks, but especially so for adding. Unlike previous studies of non-linguistic task switching, switch costs were not modulated by instruction (voluntary versus cued), and unlike with language switching (in the picture naming task), task dominance effects remained significant in both the cued and voluntary mixed-task blocks and there was no switch cost asymmetry in the cued condition (i.e., the dominant reading task did not exhibit larger cued switching costs than the non-dominant adding task).

Bilinguals responded more quickly in the read than in the add task, as indicated by a main effect of dominance, $t = 13.99$. This effect of dominance was evident in both the cued condition, $\beta = 396.4$, $SE = 28.4$, $t = 13.95$, and the voluntary condition, $\beta = 291.8$, $SE = 24.6$, $t = 11.85$ (though bilinguals made slightly more errors on voluntary read trials than on voluntary add trials; see Appendix B). Switch costs were significant overall, as indicated by a main effect of trial type, $t = 8.94$, and were significant in both the cued condition, $\beta = 75.1$, $SE = 11.9$, $t = 6.29$, and the voluntary condition, $\beta = 64.0$, $SE = 12.1$, $t = 5.29$. Relative to the cued condition, bilinguals responded more quickly in the voluntary condition, as indicated by a main effect of instruction type, $t = -6.57$.

As in the picture naming task (and unlike Arrington & Logan, 2005, in which switch costs were larger in cued than in voluntary), switch costs in the read-add task did not differ between the cued and voluntary conditions, as indicated by a non-significant interaction between trial type and instruction type, $t < 1$. As in the picture naming task, the more difficult task (in this case, adding) benefited relatively more from the voluntary versus cued instruction than the relatively easier task (reading), as shown in Figure 1b. This interaction between dominance and instruction type was significant, $t = -4.75$. Although read responses were produced much more quickly than add responses, switch costs were equally sized for the two tasks, as indicated by a non-significant interaction between trial type and dominance, $t < 1$. In other words, there was no task by switch cost asymmetry as was found for language switching, and has often been reported for non-linguistic switching between tasks that vary in difficulty (e.g., Allport et al., 1994).

The three-way interaction was significant, $t = 2.12$, reflecting a difference in switch cost asymmetries between the cued and voluntary conditions. Specifically, in the cued condition, though switch costs were numerically greater for the dominant read task than for the add

task, this interaction between dominance and trial type (i.e., the standard switch cost asymmetry) was not significant, $\beta = -23.4$, $SE = 26.6$, $t < 1$. In the voluntary condition, however, switch costs tended to be greater for the add task than for the read task (the opposite of the standard asymmetry that was observed in the picture naming task), and this interaction was marginally significant, $\beta = 37.5$, $SE = 19.2$, $t = 1.95$.

Cross-domain comparisons: Bilinguals responded faster overall in the read-add task than in the picture naming task, as indicated by a significant effect of domain, $t = -6.93$. In addition, all other main effects were modulated by domain: In the read-add task, relative to the picture naming task, switch costs were smaller, dominance effects were larger, and the effect of instruction type (the benefit for responding in the voluntary condition vs. the cued condition) was larger, as indicated by significant interactions between domain and trial type, $t = -2.35$, domain and dominance, $t = 9.64$, and domain and instruction type, $t = -4.52$, respectively.

The three-way interaction between domain, trial type, and instruction type was significant, $t = 2.69$, reflecting the fact that the standard switch cost asymmetry (larger switch costs for dominant responses) was observed in the picture naming task but not in the read-add task. No other effects varied by domain, all $ts < 1.64$.

Discussion—Based on the results of Experiment 1, the answer to the question ‘Is voluntary language switching easier than cued language switching?’ the results of Experiment 1 reveal that the answer is ‘no’ in the sense that there was no overall benefit in response speed comparing voluntary to cued language mixing.² (Note that here we refer to mixing in general considering performance overall in the mixed-language blocks, not to ‘mixing costs’ which involve comparing non-switch trials across single- versus mixed-language blocks, an aspect of performance not examined in the present study.) Although voluntary responses were faster than cued responses in the non-dominant language across stay and switch trials, the opposite pattern was observed in the dominant language (i.e., voluntary responses were slower than cued responses across stay and switch trials).

In the read-add task, the voluntary advantage was also modulated by task dominance (with a greater voluntary benefit for the non-dominant add task than for the dominant read task). However, the read-add task also differed considerably from the language task in that there was a robust overall advantage for voluntary task mixing. This result differs from that observed for the language task, and also constitutes a more robust and generalized voluntary mixing advantage than previously reported for non-linguistic switching (in which the advantage was modulated by trial type; Arrington & Logan, 2005). A priori, language control would have seemed to be the ideal candidate for an overall voluntary advantage via possible suspension of top-down control given that non-dominant language responses may

²There was an overall voluntary advantage for language in error rates (9.5% errors in the voluntary condition compared with 17.7% in the cued condition); however, this likely did not reflect a true voluntary *retrieval* advantage, but rather the fact that some low-frequency names would be unknown in the non-dominant language. (There can be no speed-accuracy trade-off on a trial for which extra time would not increase the probability of a successful retrieval.) This problem could be avoided in the voluntary block (by producing all difficult names in the dominant language; see Gollan & Ferreira, 2009), but this strategy would not be possible in the cued block.

often be relatively inaccessible, rendering cued responses (whether stay or switch) quite difficult, and given an obvious set of bottom-up forces for staying or switching within one language or the other. By contrast, both read and add responses would ultimately be accessible if given sufficient time. Thus, the failure to observe a more robust voluntary advantage for linguistic than for non-linguistic mixing (indeed, the opposite was found here) implies a significant limitation on the extent to which switches can be influenced by bottom-up processes, and a limitation on the extent to which language switches can be driven via bottom-up associations between pictures and responses in either language.

A further difference across domains was found in cued blocks in the form of a switch cost asymmetry for cued language switching but not for cued task switching. That is, bilinguals exhibited significantly larger switch costs for the dominant than the non-dominant language, but no analogous effect was found for the read-add tasks even though the read task was clearly dominant (i.e., read responses were much faster than add responses). Perhaps related to this, language dominance effects, but not task dominance effects, were eliminated (and even marginally reversed) in the mixed blocks when going from cued to voluntary instructions. The switch cost asymmetry is common in the literature for switching between tasks that vary in difficulty, and both the asymmetry and reversal or elimination of language dominance effects may reflect the mechanism of inhibitory control and its recruitment for controlling mixing of naturally competing tasks. We defer further discussion of these differences to the General Discussion.

A final difference was observed in apparent motivations to switch across domains (see Appendix A for details). Bilinguals who switched frequently enough to contribute to all four conditions in the voluntary switch block (and were thus included in statistical comparisons of cued to voluntary switching) were slower to name pictures in their dominant language, and exhibited larger cued language switching costs, than bilinguals who did not contribute data to all four conditions (and were thus excluded from analyses). By implication, language switches in the voluntary block were motivated by relative inaccessibility of picture names in the dominant language and an attempt to improve fluency via language mixing. However, voluntary mixing did not in fact improve response speed in the language task compared with dominant language-only responses. By contrast, no systematic differences were found between included versus excluded participants in the read-add task, suggesting important differences across domains in motivations for switching.

In Experiment 2, we further investigated possible cross-domain overlap in control mechanisms by again comparing cued to voluntary linguistic and non-linguistic switching, but this time with repeated presentation of a small set of items that all bilinguals could easily name in both languages. Of particular interest were possible changes in the pattern of results found for language control given the likely effects of inaccessibility of some non-dominant language names on language control in Experiment 1 (but not on non-linguistic control for which all responses were accessible in Experiment 1). We hypothesized that by removing cross-domain differences in accessibility of alternative responses greater cross-domain similarity would emerge.

Experiment 2: Cued versus Voluntary Switching With Repetition of Stimuli

Previous comparisons of cued to voluntary switching always entailed repetition of a small set of items. Language switching (and the read-add task we designed) naturally afford the possibility of examining switching behavior without massive repetition of items; however, to enable comparison to the existing literature and to provide a complete consideration of possible cross-domain similarity in control mechanisms, it is important to also examine the contrast between cued and voluntary switching as previously instantiated. In Experiment 2, bilinguals named 8 pictures with very high-frequency names multiple times in the language task, and read or added digits of 8 easy numbers multiple times in the read-add task. With repeated presentation of a small set of stimuli, we anticipated that a considerably different pattern of results might emerge for language control given that names from both languages would be highly accessible. In particular, language dominance effects should be reduced or eliminated altogether, and language switching results might more closely resemble previously reported results for non-linguistic switching tasks. On the other hand, as bilinguals would not need to name any difficult pictures, they might employ different voluntary mixing strategies given that switches would never be compelled by lack of accessibility. Under these conditions, switches might be more fully voluntary than previously tested (in Experiment 1 and in Gollan & Ferreira, 2009), thereby enabling other strategies. For example, language choice might be controlled more fully by bottom-up processes via consistent naming of some pictures in one language and other pictures in the other language. This could in turn reduce or perhaps even eliminate switch costs. (Note that switch costs are not reduced in non-linguistic switch tasks by previous exposure of stimulus-task associations, though prior exposure does significantly bias subsequent task choice; Arrington, Weaver, & Pauker, 2010.)

For the read-add task, we also expected reduced dominance effects with repetition (because more difficult tasks should improve with repetition relatively more than easy tasks), but otherwise the results should be more similar to those observed in Experiment 1 given that both read and add responses would ultimately be accessible on every trial both with and without repetition. Of general interest was whether the overall advantage for voluntary over cued switching would be replicated with repetition of read-add items. If so, and if no such voluntary advantage is found for language switching with repetition of a small set of items, this would suggest that previous comparisons of cued to voluntary switching underestimated the voluntary advantage, and possibly also that the non-linguistic nature of the tasks is critical for observing this pattern.

Methods

Participants: Sixty-eight Spanish-English bilinguals from UCSD participated for course credit. Thirty-one of these (or 46% of bilinguals tested) did not switch languages enough in the voluntary language block to produce data in the four conditions of interest (i.e., stay and switch trials in the dominant and non-dominant languages) and were excluded from the picture naming analyses. Twenty-four bilinguals (or 35% of bilinguals tested) did not switch tasks enough in the voluntary task block to produce data in the four conditions of interest (i.e., stay and switch trials in the read and add tasks) and were excluded from the read-add analyses. Following these exclusions, 28 bilinguals contributed data to both analyses, 9

bilinguals contributed data only to the picture naming analysis, and 16 bilinguals contributed data only to the read-add analysis.

Table 2b illustrates the characteristics of participants who were included and excluded from statistical analyses. All bilinguals reported learning to speak Spanish before English at home. Fifty reported being English-dominant or balanced; for these bilinguals, English responses were classified as dominant and Spanish as non-dominant. These dominance classifications were reversed for the remaining bilinguals, who reported being Spanish-dominant ($n=18$, of whom 11 were included in the picture naming task analyses)

Materials and procedure

Language task: Target picture naming stimuli included eight black-and-white line drawings of pictures that were selected so all bilinguals could easily name them in both languages (*bone-hueso*, *bread-pan*, *finger-dedo*, *foot-pie*, *glasses-lentes*, *house-casa*, *money-dinero*, and *tree-arbol*). As in Experiment 1, bilinguals named 32 pictures in an English-only condition, 32 in a Spanish-only condition, 64 in a cued switching condition (32 in each language), and 64 in a voluntary switching condition. Within each block, each of the 8 pictures was presented an equal number of times. Each condition began with 12 practice trials of picture naming (using filler pictures) to familiarize participants with the task demands. After a break in which participants were informed that they would begin, 6 practice trials with fillers (two of which were switch trials in the cued-switch condition) were followed without break or warning by the experimental trials.

In the cued-switch picture naming block, each picture was named four times in each language, of which one of those four presentations was a switch trial. Thus, the switch rate for this block was 25%. Because counterbalancing was performed within- rather than between-item (in contrast to Experiment 1), only 4 lists with 4 different pseudo-random orders were used. As in Experiment 1, in the cued switching condition, the number of pictures that could be named in each language on successive trials was limited to 6 and the number of consecutive switch trials was limited to 2.

Read-add task: Target read-add stimuli included eight numbers, all classified as easy so as to make responses for both read and add tasks readily accessible (34, 50, 80, 101, 102, 180, 1500, 4000). As in Experiment 1, bilinguals were presented with 32 numbers in a read-only block, 32 in an add-only block, 64 in a cued-switching condition (32 in each task), and 64 in a voluntary-switching condition. Within each block, each of the eight numbers was presented an equal number of times, and the number and structure of practice trials, as well as the counterbalancing constraints, was the same as for the picture naming stimuli.

All other details concerning instructions, apparatus, trial structure, and counterbalancing procedures were identical to Experiment 1.

Analysis: The same analytic procedures were followed as in Experiment 1. All fixed effects were allowed to vary by all random factors in all analyses, with two exceptions: First, effects of domain were not allowed to vary by items (because domain is a between-items factor); second, due to convergence issues, random slopes were not fitted to effects containing the

three-way interaction between dominance, trial type and instruction type in the picture naming analysis or in the cross-domain analysis. (These random slopes were dropped because exploratory analyses revealed that none of their corresponding fixed effects approached significance.)

Results—The 53 participants who switched into and stayed in each language or each task at least once provided data for 15,552 trials, of which 97.7% (15,200) were analyzed. Trials were excluded when a participant produced a response that did not match the target name or an acceptable alternative (87 picture naming trials, 173 read-add trials), when the experimenter determined that the recorded reaction time was invalid (due to, e.g., coughing or overt hesitations; 20 picture naming trials, 27 read-add trials), or when a participant responded faster than 250 ms (8 picture naming trials, 5 read-add trials) or did not respond within 3000 ms (5 picture naming trials, 35 read-add trials). (Note that some trials violated multiple criteria.) The models are summarized in Tables 5 and 6, and results are shown in Figure 1c and 1d.

Choices to switch: In the voluntary condition, included and excluded bilinguals collectively switched on 21% of picture naming trials ($SD=22\%$) and 23% of read-add trials ($SD=19\%$), thereby closely matching the switch rate in the cued condition. Although these switch rates were lower than in Experiment 1, switch rates among the participants who were included in the analyses below resembled those in Experiment 1: Bilinguals switched on 37% of picture naming trials ($SD=17\%$) and 33% of read-add trials ($SD=15\%$), which is higher than the switch rate in the cued condition.

Dominance without mixing: When naming pictures in the single-language conditions, bilinguals responded faster in their self-reported dominant than non-dominant languages, $t = 2.89$. Analogously, in the single-task conditions, bilinguals responded faster when reading than when adding numbers, $t = 2.57$. Bilinguals responded marginally faster in the read-add task than in the picture naming task, as indicated by a marginally significant effect of domain, $t = -1.95$. Unlike in Experiment 1, dominance effects for each domain did not significantly differ from each other, $t = 1.05$.

Language mixing: Cued versus voluntary: Summarizing key results: In the mixed-language blocks – in contrast to the single-language blocks – language dominance effects were not significant and switch costs were found in both cued and voluntary conditions, though these switch costs were marginally smaller in the voluntary condition.

Bilinguals named pictures faster in the voluntary block than in the cued block, as indicated by a significant effect of instruction type, $t = -2.35$, demonstrating a greater voluntary advantage for language switching over that observed in Experiment 1. They did not name pictures more quickly in the dominant than in the non-dominant language, $t < 1$; this pattern was the same for both cued blocks, $\beta = 3.9$, $SE = 12.5$, $t < 1$, and voluntary blocks, $\beta = -0.6$, $SE = 14.4$, $t < 1$. Overall switch costs were highly robust, as indicated by a main effect of trial type, $t = 6.41$. Of note, switch costs were significant both within the cued condition, $\beta = 97.6$, $SE = 21.3$, $t = 4.58$, and within the voluntary condition alone, $\beta = 48.2$, $SE = 13.7$, $t = 3.52$.

Unlike in Experiment 1, and more analogous to previous reports about non-linguistic switching, the contrast between cued and voluntary switching was modulated by trial type: On switch trials, voluntary responses were faster than cued responses, $\beta = -66.0$, $SE = 28.7$, $t = -2.30$, but there was no difference between conditions on stay trials, $\beta = -21.3$, $SE = 15.3$, $t = -1.39$ (see Figure 1c). This interaction between trial type and instruction type was marginally significant, $t = -1.69$. In addition, and again unlike in Experiment 1, the contrast between cued and voluntary switching was not modulated by language dominance, as indicated by a non-significant interaction between dominance and instruction type, $t < 1$. The interaction between dominance and trial type also was not significant, $t < 1$, as switch costs for the dominant and non-dominant language did not differ either in cued blocks, $\beta = 3.0$, $SE = 25.0$, $t < 1$, or in voluntary blocks, $\beta = 6.3$, $SE = 22.0$, $t < 1$.

As in Experiment 1, the 3-way interaction was not significant, $t < 1$.

Task mixing: Cued versus voluntary: Summarizing key results: In the mixed-task blocks, there were significant switch costs, and unlike in the picture naming task in Experiment 2, task dominance effects remained significant. In addition, there was an overall advantage for voluntary responses on both stay and switch trials, and there was a reversed switch cost asymmetry such that switch costs were greater in the less dominant (add) task.

Bilinguals responded more quickly in the read task than in the add task, and on stay trials than on switch trials, as indicated by main effects of dominance, $t = 5.22$, and trial type, $t = 4.00$, respectively. As in Experiment 1, bilinguals responded more quickly overall in the voluntary than in the cued conditions, as indicated by a main effect of instruction type, $t = -4.33$.

Unlike in Experiment 1 (and similarly to the picture naming task in Experiment 2), switch costs were significantly modulated by instruction type, as indicated by a significant interaction between instruction type and trial type, $t = -2.13$. This interaction reflects the fact that switch costs were larger in the cued block, $\beta = 58.2$, $SE = 15.1$, $t = 3.86$, than in the voluntary block, $\beta = 31.5$, $SE = 10.4$, $t = 3.03$. The three-way interaction was not significant, $t < 1$.

Also unlike in Experiment 1, and more like the picture naming results from Experiment 2, the more difficult task (adding) did not benefit more from the voluntary instruction relative to the cued instruction than the easier task (reading) in the RTs, as indicated by a non-significant interaction between dominance and instruction type, $t < 1$; responses were faster in the voluntary condition than in the cued condition for both the read task, $\beta = -65.1$, $SE = 19.0$, $t = -3.43$, and the add task, $\beta = -65.6$, $SE = 23.9$, $t = -2.75$. In contrast to the picture naming results from Experiment 2, however, task dominance effects were evident not only in the cued block, $\beta = 101.9$, $SE = 20.9$, $t = 4.87$, but also in the voluntary block for the read-add task, $\beta = 103.3$, $SE = 28.2$, $t = 3.67$ (though bilinguals made more errors on voluntary read trials than on voluntary add trials, as in Experiment 1; see Appendix B). Together, these findings could imply that inhibition of the dominant task to achieve mixing might be a control mechanism more specific to language, a possibility we discuss in the General Discussion.

An unexpected finding was that the read task exhibited smaller switch costs than the add task, as indicated by a significant interaction between trial type and dominance, $t = 4.03$. In fact, the read task exhibited no significant switch costs, either for cued switching, $\beta = 21.2$, $SE = 17.0$, $t = 1.25$, or voluntary switching, $\beta = -5.8$, $SE = 15.3$, $t < 1$. The finding that the dominant task showed smaller switch costs than the non-dominant task is the opposite of the pattern found in the Experiment 1 picture naming task, and goes against the more typical pattern in which the dominant task produces greater switch costs than the non-dominant task (for reviews, see Kiesel et al., 2010; Monsell, 2003).

Cross-domain comparisons: Two effects were significant in the read-add analysis that were not even marginally significant in the picture naming analysis: a main effect of dominance, in which participants responded faster in the (dominant) read task than the (non-dominant) add task but did not name pictures faster in the dominant than in the non-dominant language; and an interaction between dominance and trial type, in which switch costs were greater for the add task than for the read task but were equivalent for naming pictures in the dominant and non-dominant languages. Both of these cross-domain differences – the interactions between domain and dominance, $t = 4.61$, and between domain, dominance, and trial type, $t = 2.76$ – were significant. In addition, switch costs were larger for the picture naming task than for the read-add task, as indicated by an interaction between domain and trial type, $t = -2.18$. No other effects varied by domain, all $ts < 1.08$.

Discussion—The results of Experiment 2 revealed a clearer advantage for voluntary language switching over cued language switching than found in Experiment 1 and in so doing provided support for the hypothesis that lexical accessibility (or rather inaccessibility of non-dominant language names) modulates the voluntary advantage in bilingual language control. Together, the two experiments further reveal that massive repetition of a small set of items appears to magnify the extent to which control mechanisms overlap across linguistic and non-linguistic domains (though below we suggest that this apparent similarity in results might belie different underlying control mechanisms). The overall voluntary advantage emerged for language control only with repetition of a small set of items, whereas the read-add task exhibited a generalized and robust voluntary advantage both without and with repetition of items. In addition, repetition reduced voluntary switch rates in both language and read-add switching (when considering both included and excluded participants; see *Choices to Switch* in both Experiments 1 and 2).

To further consider cross-domain overlap in control mechanisms, we examined correlations between linguistic and non-linguistic domains with respect to switch rates in the voluntary switching condition, and intrusion error rates in the cued switching condition. These correlations, which included all participants tested in each experiment (both included and excluded in the analyses that compared cued to voluntary switching), are shown in Figure 2. Of interest, all of these correlations were statistically significant, but the relationship between linguistic and non-linguistic switching appeared to be stronger with repeated presentation of a small set of stimuli (in Experiment 2) than without such repetition (in Experiment 1). More specifically, in the cued switching condition, bilinguals who often failed to perform the cued task when switching between languages also failed more often to

perform the cued task when switching between reading and adding. However, this correlation was about half as strong in Experiment 1 without repetition of stimuli (Figure 2a), $r(94) = .24$, $p = .03$, than in Experiment 2 with massive repetition of just eight stimuli (Figure 2b), $r(66) = .51$, $p < .01$. Trending in the same direction (more cross-domain similarity with than without repetition), in the voluntary switching condition, bilinguals who switched languages often also chose to switch between reading and adding more often, but this correlation was weaker in Experiment 1 without repetition of stimuli (Figure 2c), $r(94) = .25$, $p = .01$, than in Experiment 2 with massive repetition of just eight stimuli (Figure 2d), $r(66) = .38$, $p < .01$. Finally, switch cost correlations between domains are shown in Table 7. Few of these correlations were significant, but to the extent that correlations were found, they were more robust with repetition of stimuli, where all five significant correlations went in the expected direction and had r values ranging from .38 to .67, than without repetition, where only one of two significant correlations went in the expected direction and they had r values of $-.26$ and $.28$.

Though cross-domain overlap in control mechanisms appeared to be somewhat greater with repetition of a small set of items, key differences remained. First, language dominance effects, but not read-over-add dominance effects, were eliminated in the voluntary blocks. The presence of significant dominance effects in single-language blocks and their reduction or elimination in the mixed-language blocks is consistent with our previous claim that bilinguals suppress the dominant language to enable language mixing (Gollan & Ferreira, 2009). The persistence of this pattern in the current study, both with and without repetition, increases confidence in this and related conclusions (i.e., that the reversal of language dominance in the voluntary mixed block might reflect suppression of the dominant language; see Figure 1a). Note that in the current study, our counterbalancing procedure of always administering single-language blocks first followed by mixed-language blocks introduced a confound that potentially undermines this conclusion (e.g., if dominance effects disappear after a certain amount of practice). However, the same pattern of results was found in Gollan and Ferreira (2009) without this confound. Moreover, the role of inhibition is supported by fully reversed dominance effects (which practice alone could not introduce) in numerous other language switching studies (e.g., Christoffels et al., 2007; Costa, Santesteban, & Ivanova, 2006; Peeters et al., 2014; Verhoef et al., 2009).

Another finding of interest in Experiment 2 was that voluntary language switching remained costly even with repeated presentation of a small number of pictures with names that are readily accessible in both languages. This result demonstrates parallels between language switching and previously published work on non-linguistic switching in showing that language switches are not a special case of switching behavior that is necessarily cost-free, nor can they be fully and completely driven by bottom-up processes of either lexical accessibility or habits of naming certain pictures in one language but not in the other. However, additional explorations presented in the remainder of this discussion section revealed cost-free language switches for a subset of the bilinguals tested in Experiment 2 – and similar explorations of the read-add task did not yield similar patterns.

Cost-Free Language-Switches, but not Read-Add Switches, for Some Bilinguals

We hypothesized that with repetition of a small set of pictures (as in Experiment 2), and with the voluntary switch instructions, bilinguals might be able to suspend top-down control over language selection, allowing switches to be driven entirely by relatively automatic stronger association of names in one language with each picture. Because switch costs were significant in the voluntary condition in Experiment 2, we seem to have ruled out this interpretation of the data for all bilinguals. However, if only some bilinguals were able to suspend top-down control, and if only these bilinguals exhibited no switch costs, this would be lost in averaging, and might even explain why – on average – switch costs were significantly smaller in the voluntary than in the cued conditions.

To consider this possibility, we divided bilinguals in Experiment 2 into two groups. In an attempt to identify bottom-up switchers – that is, bilinguals who might have voluntarily mixed languages by allowing pictures to activate one or the other language – we counted for each bilingual the number of times they named each of the eight pictures in each language. Any pictures that were named about equally often in each language (4 or 5 times in one language and 4 or 3 times in the other) were classified as top-down-switched pictures. We then counted the number of top-down pictures for each bilingual. Bilinguals with zero or one top-down pictures who named at least some pictures in each language in the voluntary mixed condition were classified as *bottom-uppers* ($n=17$). The rest of the bilinguals who were included in the Experiment 2 picture naming analysis (i.e., who named at least some pictures in each language in the voluntary mixed condition) were classified as *top-downers* ($n=20$). Relative to top-downers, bottom-uppers named significantly fewer pictures about equally often in each language (0.5 vs. 3.9), $t(22.6^3) = 7.98, p < .01$, significantly more pictures predominantly in English (4.0 vs. 2.2), $t(35) = 27.8, p = .01$, and significantly more pictures predominantly in Spanish (3.5 vs. 1.9), $t(35) = 2.71, p = .01$. Of great interest, bottom-uppers did not switch less often ($M=40\%$, $SD=15\%$) than top-downer bilinguals ($M=34\%$, $SD=18\%$) in the voluntary block; if anything they tended to switch more often (though this difference was not significant, $t(35)=1.24, p=.22$).

We then used paired t-tests to determine the significance of switch costs in the voluntary and cued conditions separately for the two groups of bilinguals. As illustrated in Figure 3, for trials included in the Experiment 2 picture naming analyses, switch costs were significant for top-downers in both the cued condition (91 ms), $t(19)=5.68, p<.01$, and the voluntary condition (70 ms), $t(19)=3.26, p<.01$, and for bottom-uppers in the cued condition (105 ms), $t(16)=5.55, p<.01$, but – crucially – not for bottom-uppers in the voluntary condition (6 ms), $t(16)<1, p=0.64$. This supports the hypothesis that some bilinguals in Experiment 2, specifically those classified as bottom-uppers, were able to avoid paying switch costs by letting relatively automatic picture-response associations drive switches based on whichever name (regardless of language) each picture activated to a greater extent than its translation equivalent. Consistent with this interpretation, bottom-uppers paid no significant switch

³Equal variances not assumed.

costs in the voluntary condition in either their dominant or non-dominant language (both $ts < 0.89$, both $ps > .38$). In contrast, top-downers paid significant switch costs in the voluntary condition in both languages (both $ts > 2.37$, both $ps < .03$).

Finally, we considered whether the advantage of voluntary over cued language switching might be driven entirely by bottom-uppers. This was accomplished by fitting the mixed-effects model reported in Experiment 2 on picture naming data separately for bilinguals in each naming strategy group. In these analyses, bottom-uppers exhibited a marginally significant interaction between instruction type and trial type akin to the one reported in Experiment 2, such that switch costs were marginally smaller in the voluntary than in the cued condition, $\beta = -78.2$, $SE = 40.5$, $t = -1.93$. However, as this interaction may not have reached full significance due to moderate collinearity ($r > .3$) with other effects in the model, model comparison was used to evaluate the significance of the effect (Barr et al., 2013). In support of this hypothesis, the model for bottom-uppers reported above fit the data significantly better than a model with the same random effects structure and all of the same fixed effects except the interaction between instruction type and trial type, $\chi^2(1) = 13.86$, $p = .0002$, suggesting that, indeed, bottom-uppers' switch costs were significantly smaller in the voluntary condition than in the cued condition. In contrast, this interaction did not approach significance in the top-downer bilinguals, $\beta = -22.4$, $SE = 46.7$, $t < 1$, and this lack of significance was not due to collinearity, as evidenced by the lack of a significant improvement in model fit, $\chi^2(1) = 0.81$, $p = .37$. Together, these analyses suggest that in language switching, an advantage for voluntary over cued switches emerges only for bilinguals who suspend top-down control over language selection, and furthermore that some of the apparent similarity that emerges across domains with repetition of items might be caused by different underlying cognitive mechanisms (i.e., similar data patterns but without overlap in control mechanisms across domains).

An analogous division of bilinguals from the read-add task in Experiment 2 into bottom-uppers ($n=13$) and top-downers ($n=31$) yielded significant switch costs in both cued and voluntary conditions for both bottom-uppers and top-downers (all $ts > 2.13$, all $ps < .05$). The means for this analysis are shown in Table 8. Switch costs for each task were nearly identical for the two groups of bilinguals in the voluntary block. To the extent that any differences between groups emerged, it was in the cued block, where bottom-uppers showed larger switch costs for the read task than top-downers (46 ms vs. 10 ms, respectively); however, switch costs were similarly sized across tasks in cued and voluntary blocks for each group of bilinguals (i.e., there was no interaction between instruction type and trial type for either group; both $ts < 1$). Thus, the possibility of task mixing via relatively automatic association between stimuli and associated responses did not generalize outside the domain of language. Cost-free switches might need to be driven by *a priori* associations between stimuli and their responses, associations that would not exist for adding responses to the numbers.

Having identified a number of significant cross-domain differences, a final question that remained was the extent to which the differences we identified represent true differences across domains versus possibly idiosyncratic differences associated with the tasks as implemented here. We designed the read-add task to enable comparisons across domains

while avoiding as much as possible methodological differences across task implementations in each domain. However, this introduced a number of potentially important differences relative to canonical implementations of non-linguistic task switching. Most obviously, this included the use of vocal instead of button-pressed responses, the option to examine voluntary switching behaviors without repetition of items, and the testing of bilinguals (who can switch languages).

Experiment 3: Cued versus Voluntary Switching in Monolinguals with Repetition

Experiment 3 was designed to reveal effects possibly specific to bilinguals in non-linguistic task switching, or patterns that might be idiosyncratic to the read-add task relative to tasks more commonly examined in the literature on voluntary task switching. To do this, we tested monolinguals on the read-add task from Experiment 2 and compared their performance on this task to the commonly assessed task of switching between size and parity judgments. Although the size-parity task is typically implemented with button press responses, participants responded vocally to maximize comparability with Experiments 1 and 2.

Methods

Participants: One hundred and four English-speaking monolinguals from UCSD participated for course credit. Forty-two of these (or 40% of monolinguals tested) did not switch tasks enough in the voluntary size-parity block to produce data in all four conditions of interest (i.e., stay and switch trials in the size and parity tasks) and were excluded from the size-parity analysis. Forty-five monolinguals (or 43% of monolinguals tested) did not switch tasks enough in the voluntary read-add block to produce data in all four conditions of interest (i.e., stay and switch trials in the read and add tasks) and were excluded from the read-add analyses. In addition, to facilitate model convergence, two monolinguals with a large number of errors and missing data points (>45%) in both tasks were excluded from both analyses. Following these exclusions, 52 monolinguals contributed data to both analyses, 8 monolinguals contributed data only to the size-parity analysis, and 5 monolinguals contributed data only to the read-add analysis.

Table 2c illustrates the characteristics of participants who were included and excluded from statistical analyses.

Materials and procedure

Size-parity task: Target size-parity stimuli were the digits 1, 2, 3, 4, 6, 7, 8 and 9 (Arrington & Logan, 2005). In the size task, participants said “smaller” if the presented digit was smaller than 5 and “bigger” if the presented digit was larger than 5. In the parity task, participants classified the parity of the presented digit by saying “even” or “odd”. Thus, among the eight digits, every combination of size category and parity was represented an equal number of times (twice). Analogously to Experiments 1 and 2, monolinguals named 32 digits in a size-only condition, 32 in a parity-only condition, 64 in a cued switching condition (32 in each task), and 64 in a voluntary switching condition. Within each block, each of the 8 digits was presented an equal number of times. Each condition began with 8 practice trials to familiarize participants with the task demands. After a break in which

participants were informed that they would begin, 8 practice trials (three of which were switch trials in the cued-switch condition) were followed without break or warning by the experimental trials. In both sets of practice trials, every critical stimulus was shown once.

In the cued-switch size-parity block, each digit was categorized four times in each task, of which one of those four presentations was a switch trial. Thus, the switch rate for this block was 25%. As in Experiment 2, only 4 lists with 4 different pseudo-random orders were used. As in Experiments 1 and 2, in the cued switching condition, the number of digits that could be categorized in each task on successive trials was limited to 6 and the number of consecutive switch trials was limited to 2.

Read-add task: All details concerning the read-add task, as well as the instructions, apparatus, trial structure, and counterbalancing procedures, were identical to Experiment 2.

Analysis: The same analytic procedures were followed as in Experiments 1 and 2. All fixed effects were allowed to vary by all random factors, with two exceptions: First, effects of non-linguistic task set (i.e., read-add versus size-parity) were not allowed to vary by items (because this is a between-items factor); second, due to convergence issues, the four-way interaction and all three-way interactions in the cross-task set analysis that included an effect of dominance were not allowed to vary by either participants or items in that analysis. (These random slopes were dropped because exploratory analyses revealed that none of their corresponding fixed effects approached significance.)

Results—The 65 participants who switched into and stayed in both the size and parity tasks at least once, or who switched into and stayed in both the read and add tasks at least once, provided data for 22,464 trials, of which 96.6% (21,696) were analyzed. Trials were excluded when a participant produced a response that did not match the target name or an acceptable alternative (225 size-parity trials, 182 read-add trials), when the experimenter determined that the recorded reaction time was invalid (due to, e.g., coughing or overt hesitations; 30 size-parity trials, 17 read-add trials), or when a participant responded faster than 250 ms (148 size-parity trials, 132 read-add trials) or did not respond within 3000 ms (6 size-parity trials, 40 read-add trials). (Note that some trials violated multiple criteria.) The models are summarized in Tables 9 and 10, and results are shown in Figure 1e and 1f.

Choices to switch: In the voluntary condition, included and excluded monolinguals collectively switched on 18% of size-parity trials ($SD=19\%$) and 20% of read-add trials ($SD=19\%$). Among the participants who were included in the analyses below, monolinguals switched on 31% of size-parity trials ($SD=15\%$) and 32% of read-add trials ($SD=14\%$), which is higher than the switch rate in the cued condition (similar to Experiments 1 & 2).

Dominance without mixing: When responding to the size or parity of digits in the single-task conditions, monolinguals responded faster in the dominant task (size judgment) than in the non-dominant task (parity judgment), $t = 4.43$. Analogously, they responded faster when reading than when adding numbers, $t = 3.42$. These dominance effects were equivalent, as indicated by the non-significant interaction between domain and dominance, $t = 1.47$.

Cued versus voluntary size-parity mixing: In the mixed-size-parity block, monolinguals responded faster in the size task than in the parity task, faster on stay trials than on switch trials, and faster in the voluntary switching condition than in the cued switching condition, as indicated by main effects of dominance, $t = 3.65$, trial type, $t = 7.61$, and instruction type, $t = -3.33$, respectively.

As dominance effects were similarly sized in the cued condition, $\beta = 55.9$, $SE = 13.5$, $t = 4.14$, and the voluntary condition, $\beta = 39.9$, $SE = 15.6$, $t = 2.55$, the interaction between dominance and instruction type was not significant, $t = -1.23$. Although switch costs were significant in both the cued condition, $\beta = 83.3$, $SE = 10.5$, $t = 7.95$, and the voluntary condition, $\beta = 30.1$, $SE = 10.2$, $t = 2.96$, they were significantly larger in the cued condition, as indicated by a significant interaction between instruction type and trial type, $t = -3.62$. This interaction was largely driven by a difference between conditions on switch trials, as responses were only marginally faster in the voluntary condition than in the cued condition on stay trials, $\beta = -16.5$, $SE = 9.1$, $t = -1.82$, but were significantly faster on switch trials, $\beta = -69.2$, $SE = 16.2$, $t = -4.26$. No other interactions were significant, both $ts < 1$.

Cued versus voluntary read-add mixing: In the mixed-read-add block, monolinguals responded faster in the read task than in the add task, faster on stay trials than on switch trials, and faster in the voluntary than in the cued switching condition, as indicated by main effects of dominance, $t = 4.06$, trial type, $t = 4.01$, and instruction type, $t = -5.44$, respectively.

Dominance effects were similarly sized in the cued condition, $\beta = 69.1$, $SE = 16.6$, $t = 4.16$, and the voluntary condition, $\beta = 55.3$, $SE = 20.7$, $t = 2.67$ (though monolinguals made more errors on voluntary read trials than on voluntary add trials, as in Experiments 1 and 2; see Appendix B); thus, the interaction between dominance and instruction type was not significant, $t = -0.57$. Switch costs were significant in both the cued condition, $\beta = 31.4$, $SE = 13.4$, $t = 2.35$, and the voluntary condition, $\beta = 32.7$, $SE = 8.3$, $t = 3.96$; in contrast to the pattern found for the size-parity task, these switch costs did not differ, as indicated by a non-significant interaction between trial type and instruction type, $t < 1$. Unlike in Experiment 2, read and add tasks did not exhibit a reversed asymmetry of switch costs (26 ms vs. 35 ms, respectively), as indicated by a non-significant interaction between trial type and dominance, $t < 1$. No other interactions were significant, all $ts < 1$.

Cross-task set comparisons: Although the same pattern of main effects was found in the size-parity tasks and the read-add tasks, some of the effect sizes were different. Relative to the size-parity tasks, switch costs were smaller in the read-add tasks, as indicated by a significant interaction between task set and trial type, $t = -2.45$, and the benefit of voluntary instructions over cued instructions was larger in the read-add tasks, as indicated by a significant interaction between task set and instruction type, $t = -2.72$.

As noted above, switch costs were larger for the cued switching condition than for the voluntary switching condition in the size-parity tasks but not in the read-add tasks. This difference was reflected in a three-way interaction between task set, trial type, and

instruction type, $t = 2.42$. No other effects differed in size between the size-parity and read-add tasks, all $ts < 1.64$.

Discussion—The results of Experiment 3 confirm a robust overall advantage for fully voluntary over cued switching in non-linguistic tasks that appears to be more generalized than that observed in prior investigations. With repeated presentation of a small set of stimuli, in all tasks tested there was a robust overall advantage for voluntary over cued switching. The reduction of switch costs in voluntary versus cued blocks (as opposed to a generalized advantage for voluntary over cued) appeared to vary with task and possibly also with participant type; this interaction was marginally significant for language control and significant for the read-add tasks in Experiment 2, and also significant for size-parity with monolinguals in Experiment 3, but not significant for the read-add tasks with monolinguals in Experiment 3. Without repetition (in Experiment 1), the voluntary advantage was not modulated by trial type.

In addition, only language dominance effects were reduced, eliminated, or reversed when comparing single- to mixed-language blocks in Experiments 1 and 2. In contrast, dominance effects remained significant in all single and mixed blocks for all non-linguistic tasks in Experiments 1–3 (read faster than add in Experiments 1–3, and size faster than parity in Experiment 3). Thus, the elimination (or reversal) of task dominance effects appears to be a phenomenon specific to bilingual language control.

Finally, for both bilinguals and monolinguals, the read task sometimes exhibited cost-free switches. The absence of switch costs was apparent both in RTs (for bilinguals in both cued and voluntary blocks in Experiment 2, and for monolinguals in the cued block in Experiment 3) and error rates (relative to read-stay trials, error rates on read-switch trials were only 0.22% greater for Experiment 1, 0.63% greater for Experiment 2, and 1.73% greater for Experiment 3; see Appendix B).

General Discussion

The current study compared cued and voluntary language switching and non-linguistic switching with the goals of revealing factors that make switches more or less efficient, and the extent to which linguistic and non-linguistic switching involve shared underlying cognitive mechanisms. In Experiment 1 bilinguals switched between naming pictures in English or Spanish, and between reading or adding individual digits of two-, three-, and four- digit numbers. In both domains we used a large set of materials so that switching could be examined *without* massive repetition of stimuli – a major distinction relative to previous investigations of non-linguistic task switching. Additionally, we implemented a more fully voluntary switching instruction than in previous studies by allowing participants to select which task they performed on each trial without requiring that they perform each task an approximately equal number of times, and without requiring them to attempt to maintain a “random” pattern of task alternation (Arrington, 2008; Arrington & Logan, 2004, 2005; Demanet, Liefoghe, & Vandierendonck, 2010; Liefoghe, Demanet, & Vandierendonck, 2009; Mayr & Bell, 2006). Our goal was to determine if these reductions in requirements for

top-down monitoring of voluntary choice behaviors might elicit cost-free voluntary switches, or greater voluntary advantages than previously found.

Experiment 1 revealed some striking differences between linguistic and non-linguistic domains, and relative to previously reported advantages for voluntary over cued switching. Most notably, there was a robust overall advantage for voluntary over cued responses in the read-add tasks but not in language control. In previous studies the voluntary advantage was limited exclusively to switch trials or was an artifact of cued non-switch trials being faster than voluntary non-switch trials (Arrington & Logan, 2005). The emergence of a broader overall voluntary advantage for non-linguistic switching likely reflects our suspension of various requirements on when and how often task alternations should be executed in the voluntary block and is important for developing a full understanding of the balance of labor between bottom-up and top-down control mechanisms in switching behaviors. In particular, previous instantiations of voluntary switching seem to have overestimated the costs associated with top-down control. In addition, the absence of a similar finding for language switching in Experiment 1 implies substantial differences in control mechanisms utilized across domains.⁴

In Experiment 2 we investigated the possibility that response accessibility – and more specifically inaccessibility of responses in the non-dominant language – may alter the nature of control mechanisms involved in switching by presenting a small set of highly accessible items repeatedly in both domains. This seemingly small change increased cross-domain similarity in a number of ways. First, a significant overall voluntary over cued advantage emerged in both linguistic and non-linguistic domains. In addition, the voluntary advantage was significantly greater for switch than for stay trials in the read-add tasks, and this interaction was marginally significant in language switching. Correlations across domains between switch rates (choices to switch) in the voluntary blocks, and between intrusion error rates in cued blocks, also tended to be somewhat stronger with than without repetition of items (particularly for intrusion errors; see Figure 2). These observations imply that difficulties with accessibility of responses influence both choice behaviors (decisions to switch or not) and could also affect strategies for managing competition between tasks (as indexed by the rate of intrusion errors). Of note, choices to switch voluntarily were lower with repetition in both domains (comparing Experiments 1 and 2 for both included and excluded participants), suggesting that similar factors, perhaps related to response

⁴Though we suggest that cross-domain differences outnumber similarities in Experiment 1, in both domains the more difficult task benefited more from the voluntary instruction than the easier task. The consistent modulation of the voluntary benefit by task difficulty could reflect response inaccessibility and its influence on tradeoffs between top-down and bottom-up control processes. In cued blocks, cues force retrieval of relatively inaccessible responses (in a non-dominant task or language) and this requires top-down control to initiate a less automatic series of operations (e.g., as needed to add numbers, or to retrieve a low-frequency word). Beyond this similarity, different operations will be needed to retrieve relatively inaccessible items across domains. In language switching, the dominant language seems to take on a “default for difficult responses” role, whereas non-dominant responses seem to take a “select whenever more or less possible” approach (see Experiment 1 and Gollan & Ferreira, 2009). Outside the domain of language, there may be no default mode for division of labor between dominant and non-dominant tasks. Consistent with this, the frequency with which participants selected each language and task among voluntary block trials included in the main analyses of Experiments 1–3 reveals that the dominant language was used on the majority of picture naming trials (62% and 57% in Experiments 1 and 2, respectively, both significantly different from 50%, both $t_s > 2.61$, both $p_s < .02$), whereas the dominant task – read (in read-add) and size (in size-parity) – was used relatively less often (on between 47% and 54% of trials in Experiments 1–3, none significantly different from 50%, all $t_s < 1.83$, all $p_s > .07$). The lack of a default option in non-linguistic task switching could explain why the dominant task benefited from the voluntary instruction more consistently in the read-add task than in language switching.

accessibility, motivate voluntary switches across domains; with repetition of all highly accessible items, switch rates go down. Repetition could also play a role in the extent of competition between languages; consistent with this possibility, intrusion error rates were slightly higher in the read-add task with than without repetition ($M=1.4\%$, $SD=1.2\%$ vs. $M=0.9\%$, $SD=1.2\%$), a marginally significant difference, $t(27) = -1.86$, $p = .07$. However, in the language task intrusion error rates were about the same with and without repetition ($M = 0.9\%$, $SD=1.2\%$ and $M=0.9\%$, $SD=1.3\%$, respectively, $t(61) = 0.53$, $p = .60$), suggesting that alternative responses may already be at a maximum degree of competition for language both with and without repetition.

Correlations of switch costs across domains also appeared more robust with repetition (i.e., these were significant only with repetition of a small set of stimuli and in the voluntary blocks; see Table 7⁵). Note that repetition of a small set of items does not automatically lead to correlations across domains. Calabria, Hernández, Branzi, & Costa (2012) tested Catalan-Spanish-English trilinguals on language switching (with repeated presentation of eight pictures) and on a color-shape judgment task, and found that switch costs were not correlated across domains (see also Yim & Bialystok, 2012). Several methodological differences between studies could explain the difference in results. Most notably, in the current study, non-linguistic switching did not require button-pressed responses (see also Prior & Gollan, 2013). Correlations between linguistic and non-linguistic domains may be more easily observed when examining measures other than switch costs, given that these represent notoriously noisy difference scores (Kopp, 2011; Miyake, Emerson, & Friedman, 2000), and when response modalities are equated (vocal responses for both). Cross-domain sharing of control mechanisms may be most possible at beginning and end points of control processes, such as when deciding whether to stay or switch; when setting task goals based on a cue, which happen relatively early in the sequence; and when engaging in error prevention processes (i.e., monitoring), which happen relatively late (just before response execution). In contrast, middle-stage processes that actually initiate and execute the task change may necessarily be more domain-specific, and may determine the magnitude of switch costs relatively more than the end-point operations just described.

Experiment 3 compared monolingual performance on the read-add tasks to more commonly examined switches between size and parity judgment tasks. The goal was to investigate possibly idiosyncratic aspects of the read-add task that was employed here to maximize methodological matching of the contrast between linguistic and non-linguistic switching (including vocal instead of button-pressed responses). The results of this study confirmed the broader overall advantage relative to previous studies associated with voluntary switching for both non-linguistic task sets (i.e., read-add and size-parity). In addition, they suggested that the appearance of a voluntary advantage in the form of a reduction in switch costs may vary with participant type, or with task set (see Discussion of Experiment 3).

⁵The correlations shown in Table 7 also have relevance for a debate concerning the extent to which control mechanisms overlap across cued and voluntary switching (e.g., Logan & Bundesen, 2003; Logan, et al., 2007; Monsell & Mizon, 2006). In this respect, it is notable that switch costs across tasks don't produce consistent correlations within cued or voluntary paradigms. Given that within-paradigm correlations are weak and inconsistent, it seems preferable to avoid interpreting the absence of cross-paradigm correlations (i.e., between cued and voluntary).

Importantly, the robust overall voluntary advantages we obtained could not be attributed to differences in switch rates across conditions. In cued conditions, switch rates were 25%. It seems reasonable to assume that it is more difficult to execute a block of trials with a greater number of switches than a block of trials with a smaller number of switches. After excluding participants with very low switch rates (who did not provide data in all critical cells) from data analyses, switch rates were higher in the voluntary than in the cued conditions in all three experiments (>30% in all cases). Thus, the advantage for voluntary over cued responses was obtained despite *higher* rates of switching in voluntary than in cued conditions. If the assumption that high switch frequency increases difficulty is accurate, then the current results may still underestimate the extent to which voluntary control is easier than cued control. Previous work implied that deciding whether to switch or not requires more processing resources than initiating a required task repetition (e.g., because cued stay responses were faster than voluntary stay responses; Arrington & Logan, 2005). The current data demonstrate that with more fully voluntary switching, top-down control requires fewer processing resources than following mandatory instructions to shift: It's easier to do what you want than to be told what to do.

Can Switches Ever Be Cost-Free? Bottom-Up versus Top-Down Contributions to Switching

Arrington and Logan (2005) argued that there is little evidence to support the possibility of cost-free and fully bottom-up switches. Together, the experiments presented here reaffirm that switching is only very rarely cost-free, and suggest that cost-free switches may be restricted to highly automatic (possibly linguistic) responses. A priori, we reasoned that language alternation might constitute the most obvious domain in which cost-free switches could be observed. Bilinguals regularly mix languages voluntarily, and it seemed that strong bottom-up constraints such as greater accessibility of certain names in one or the other language might have triggered switches relatively automatically without requiring decision-making or planning and without eliciting switch costs. The observation of robust switch costs in both Experiments 1 and 2 argues against the notion of language control as a special case in which switches are necessarily cost-free.

A possible exception to this rule was found in our post hoc analysis of naming strategies. With repetition of items (in Experiment 2), some bilinguals seemed able to rely on relatively automatic associations between pictures and names in one or the other language to exercise voluntary control over whether or not they switched. These bottom-upper bilinguals (see Figure 3) exhibited switch costs only when their choice of language was determined exogenously (i.e., by a cue). In contrast, top-downer bilinguals exhibited equally sized switch costs in both cued and voluntary conditions. Similar analyses of the read-add task indicated no differences in switch costs between bottom-upper and top-downer bilinguals for voluntary blocks. (Indeed, to the extent that any differences were apparent, they were in the cued blocks, where switch costs in the read task were *larger* for bottom-upper bilinguals, see Table 8.) Even so, there was some evidence for cost-free switches in the read task for both bottom-upper and top-downer bilinguals. Thus, it appears that cost-free switches might not be restricted to language per se, but possibly to highly automatic responses, which may include both language and reading. (We have used the term *non-linguistic* to refer to

anything other than language switching; of course, any task with vocal responses is more linguistic than a task with manual responses, but cost-free switches might not necessarily need to be restricted exclusively to the domain of language or to linguistic responses.)

A further suggestion towards the presence of broad limitations on the extent to which switches can be fully bottom-up is suggested by the fact that voluntary task-mixed responses (averaging over stay and switch responses) were never faster than dominant single-task responses in any experiment, a pattern of results that would have provided very strong evidence for the greater overall efficiency of voluntary control. Thus, task mixing is never sufficiently bottom-up in either linguistic or non-linguistic domains so as to be ultimately more efficient than single-language or single-task performance. By implication, all responses – whether linguistic or not, cued or not, switched or not, repeated or not, and in actively competing response sets or not – must ultimately pass through a top-down process of some kind before being executed, perhaps a monitor that checks that planned responses match the intended goals (such as the Supervisory Attentional System proposed by Green, 1998; Shallice & Burgess, 1996; and with a further stipulation that no – or only very few – cognitive tasks are sufficiently automatic to bypass this monitor fully). In the domain of language, where translation equivalents constitute virtually interchangeable responses, monitoring might be especially necessary to prevent bilinguals from producing words in the non-target language (Gollan, Sandoval, & Salmon, 2011; Poulisse & Bongaerts, 1994) or could develop for any two tasks that are in constant competition. This reasoning is in line with proposals that similar top-down processes are involved in both voluntary and cued switching, and goes against the idea that cued switches are driven entirely by bottom-up processes and do not involve top-down control (e.g., see discussion in Logan, Schneider, & Bundesen, 2007).

Further investigation might reveal why only some bilinguals appeared to employ the bottom-up naming strategy. It might seem that executive control ability should play a role here such that stronger executive control might lead to better ability to select more efficient naming strategies, or suspension of top-down control processes might be possible only at high levels of executive control ability. However, bottom-upper and top-downer bilinguals exhibited equally sized cued-switch costs, and also did not differ on most self-reported and individual difference measures (including age, age of acquisition of English, self-rated English and Spanish proficiency levels, percent of current use of English, percent of use of English as a child, picture naming test scores in English and in Spanish, and a Matrix reasoning test, all $ps > .30$). The ability to rely on bottom-up associations to control voluntary switches may instead depend on more idiosyncratic factors related to which pictures have strong associations with one or the other language. Such associations could vary across lexical items for different bilinguals. On this view, top-downer bilinguals in the current study might have been bottom-uppers if different pictures had been presented in Experiment 2. The only exception was that bottom-upper bilinguals reported switching languages marginally less often ($M=2.6$, $SD=1.5$) than top-downer bilinguals ($M=3.4$, $SD=1.2$, $p=.09$; on a scale in which 1=almost never; 2=occasionally; 3=switch 2–3 times in each conversation; 4=switch several times per conversation; and 5=often, and sometimes even constantly, switch languages when speaking to bilinguals). However, if anything, bottom-

upper bilinguals tended to switch *more* often in the voluntary condition than top-downer bilinguals. Additional work is needed to determine how habitual switching frequency may or may not lead to more efficient switching (Rodríguez-Fornells, Krämer, Lorenzo-Seva, Festman, & Münte, 2012; Soveri, Rodríguez-Fornells, & Laine, 2011), and whether or not such efficiency can transfer across tasks and domains (e.g., see Prior & Gollan, 2011; 2013). Naturally occurring switches may improve switching ability in general (leading to smaller cued switch costs) only when practiced switches are costly top-down switches.

The Role of Inhibitory Control

One potentially critical difference between linguistic and non-linguistic switching is that a bilingual's two languages may arguably constitute the most naturally competing response types. Although many bilinguals use their different languages in different environments (e.g., in the workplace vs. at home), their abilities to express thoughts are largely interchangeable across languages. Furthermore, they naturally mix languages in some settings, which would mean they have some real-world practice with the task being examined in switching studies. As noted in the introduction, switch costs in cued switching tasks are often larger for the more difficult than for the easier task, a phenomenon known as the *switch cost asymmetry*. Asymmetries have often been interpreted as the signature of inhibitory control of the dominant language in models of bilingual language control (Green, 1986; 1998; see also Philipp, Gade, & Koch, 2007; Philipp & Koch, 2009). Although it is possible to explain switch cost asymmetries without assuming inhibition (e.g., Verhoeft et al., 2009; Yeung & Monsell, 2003), we have suggested that elimination of dominance effects (or their reversal; Gollan & Ferreira, 2009) constitutes more straightforward evidence for inhibitory control. Others have similarly questioned whether the asymmetry of switch costs should be viewed as the main form of support for the inhibitory control model (e.g., Bobb & Wodnieka, 2013; Kroll, Bobb, Misra, & Guo, 2008).

In the current study, we found significant language dominance effects in single-language blocks in both Experiments 1 and 2, and these dominance effects were eliminated in voluntary (but not cued) mixed-language blocks in Experiment 1 as well as both cued and voluntary mixed-language blocks in Experiment 2. In contrast, non-linguistic switching tasks (read-add for bilinguals in Experiments 1 and 2, and both size-parity and read-add for monolinguals in Experiment 3) exhibited significant dominance effects (read faster than add, size faster than parity) that were not eliminated in either cued or voluntary mixed-task blocks. These results suggest that bilinguals inhibit the dominant language to enable language mixing, but that such inhibition of the dominant task is not a feature of non-linguistic task control. Similarly, we obtained the standard switch cost asymmetry only with cued language switching without repetition (in Experiment 1), and no analogous asymmetry with similar conditions for cued non-linguistic switching. For bilinguals in Experiment 2, there was even a significant asymmetry in the opposite direction (larger switch costs for the more difficult add task than for the easier read task). In a series of studies that investigated the switch cost asymmetry, Yeung and Monsell (2003) also found reversed switch cost asymmetries, albeit only when non-linguistic tasks did not overlap in response categories and modalities. They concluded that standard asymmetrical switch costs are obtained consistently only in conditions that maximize interference between tasks (e.g., with

overlapping response sets and modalities). The present results suggest that asymmetries may be more likely to occur between naturally competing response sets (e.g., between languages but not between reading/adding or size/parity judgments; the latter showed no asymmetry in cued or voluntary switching, all $t_s < 0.9$).⁶

This possibility raises the question of why no asymmetries were observed for voluntary language switches in Experiments 1 and 2, and also not for cued language switches in Experiment 2. The latter result might be attributable to massive repetition of a small set of pictures. Repetition might increase competition between alternative responses, and in particular might increase accessibility of non-dominant responses (which cannot compete for selection when inaccessible). If so, both dominance effects and the switch cost asymmetry should be reduced. Indeed, repetition eliminated language dominance effects (comparing Experiments 1 and 2). Importantly, the asymmetry is not always found for bilinguals with one language significantly more dominant than the other. Christoffels et al. (2007) also observed symmetrical switch costs for Dutch-English bilinguals who were clearly Dutch-dominant (though in that study there was also a striking mixing cost asymmetry, as language dominance reversed completely in the mixed-language block such that bilinguals responded more slowly in their usually dominant language). Similarly, Linck, Schwieter, and Sunderman (2012; Schwieter & Sunderman, 2008) have suggested that lexical robustness – rather than language dominance at the whole-language level – determines whether switch costs are symmetrical or asymmetrical (for similar evidence within a single language, see Finkbeiner et al., 2006, Experiment 3). Further work is needed to reveal when and why the switch cost asymmetry appears instead of eliminated or reversed dominance effects. A broader conclusion that can be drawn here is that caution should be exercised when interpreting the presence or absence of switch cost asymmetries or other similarly nuanced effects across domains (e.g., an overall voluntary advantage versus a reduction in switch costs) given that idiosyncratic methodological differences between how these are implemented (e.g., Calabria et al., 2012) may alter the nature of the effects observed (Yehene & Meiran, 2007), possibly masking cross-domain overlap in underlying control mechanisms.

Why Do Bilinguals Switch?

Several observations seem to confirm prior conclusions that switching languages is rarely more efficient than not switching, including the observation of significant switch costs in both cued and voluntary language switching and in predictable switching (Declerck, Philipp,

⁶Word frequency may also play a role in determining when switch cost asymmetries appear. To explore this possibility and the effects of frequency more generally, naming latencies in the Experiment 1 picture naming task were reanalyzed separately for each instruction type using mixed-effects models that added (log) picture name frequency, and its interactions with the effects of dominance and trial type, as fixed effects. (Apart from intercepts for participants and items, the random effects structure was limited to frequency and its interactions, which were allowed to vary by participants.) In the cued block, relative to pictures with lower-frequency names, pictures with higher-frequency names were named faster, $\beta = -65.2$, $SE = 9.1$, $t = -7.14$, showed smaller dominance effects, $\beta = -47.4$, $SE = 10.1$, $t = -4.72$, and showed a smaller switch cost asymmetry, $\beta = 54.5$, $SE = 22.3$, $t = 2.44$. A median split on picture name frequency revealed that this three-way interaction between dominance, trial type, and word frequency reflected a switch cost asymmetry for pictures with lower-frequency names, $\beta = -181.3$, $SE = 63.0$, $t = -2.88$, but not for pictures with higher-frequency names, $\beta = -18.7$, $SE = 37.5$, $t < 1$. In the voluntary block, a main effect of frequency was observed, $\beta = -61.7$, $SE = 8.7$, $t = -7.08$; however, frequency did not modulate any other effects, all $t_s < 1.08$. The modulation of the switch cost asymmetry by word frequency is unexpected on the assumption that bilinguals inhibit the dominant language as a whole (Green, 1998), and requires some revision to notions of how inhibition is used in bilingual language control (Kleinman & Gollan, 2014).

& Koch, 2013), as well as the finding that only a small subset of bilinguals tested (bottom-upper bilinguals) exhibit no voluntary switch costs. At best, switching appears to sometimes be a cost-free option that bilinguals can employ. However, important differences remain between naturally occurring switches and the switches studied here, most obviously the absence of connected speech and grammatical encoding (Bullock & Toribio, 2009; Dussias, 2003; Gollan, Schotter, Gomez, Murillo, & Rayner, 2014), and the absence of naturalistic cues to switching (e.g., Li, Yang, Scherf, & Li, 2013; Zhang, Morris, Cheng, & Yap, 2013). Nevertheless, some additional insights about what motivates switches can be gained from the observation that repetition reduced the rate of voluntary choices to switch (when considering both included and excluded participants). This was true in both linguistic and non-linguistic switching, and suggests that switches are sometimes preferred to avoid retrieval difficulty. A unique possibility for language switching might be that although language switches are costly in time, the decision to switch may shift processing burdens away from the language system to outside the language system. If so, and if speakers decide whether to switch languages or not exclusively based on linguistic processing difficulty, then language-switched responses may in fact seem easier to speakers despite the costs paid in time (because the costs are paid outside the language system).

Conclusions

The current study examined switching behavior broadly with both cued and voluntary instructions, across linguistic and non-linguistic domains, and with a variety of tasks (picture naming, read-add, size-parity) and populations (bilinguals and monolinguals) while controlling some factors that in previous work varied idiosyncratically across studies (repetition, dominance effects, and vocal versus manual responses) and allowing greater freedom in the extent to which switches were voluntary.

The current implementations of voluntary versus cued switching revealed a clearer advantage than previously reported for self-initiated over cue-elicited responses, and also revealed some rare circumstances in which switches appeared to be cost-free, controlled in a fully bottom-up, stimulus-triggers-response fashion. Fully bottom-up switches may be possible only for highly automatic tasks such as language switching (for some but not all cases) and reading, or perhaps other highly automatic tasks with strong pre-existing associations between stimuli and particular responses (perhaps also including life-saving tasks, such as switching from strolling along to sprinting out of the path of an oncoming bulldozer). Aside from these rare situations, it appears that more often than not, all responses, whether linguistic or not, pass through an executive gatekeeper or goal-check of some kind.

Another general conclusion was that across experiments, the precise manifestation of the voluntary-over-cued advantage varied (sometimes appearing as an overall advantage, and other times only on switch trials) and small changes in task implementation appeared to lead to great changes in the pattern of results obtained (both within the current study and in comparison to previous studies of voluntary switching). In a similar vein, we suggested that massive repetition of items may artificially magnify apparent similarities across domains in the control mechanisms that enable switching, and that overall in the current study, linguistic

and non-linguistic switching mechanisms appeared to differ more than they resembled each other. This leaves open the possibility of some sharing of control mechanisms across domains (Chiu & Yantis, 2009; Weissberger, Wierenga, Bondi, & Gollan et al., 2012), but also suggests that domain-specific mechanisms dominate (Calabria et al., 2012; Weissberger, et al., 2012; Yim & Bialystok, 2012). Possible domain-specific mechanisms might include a greater role for inhibitory control in the linguistic than in non-linguistic switching, and differences in the balance of labor between response alternatives with the dominant language taking on a “default” response role but with no analogous role for alternation between non-linguistic tasks (even with one clearly dominant set of responses). Future investigations of points of possible overlap in control mechanisms across domains might best be served by broadening focus away from switch costs and other difference scores, which are notoriously noisy and have produced mixed results (e.g., see Hilchey & Klein, 2010; Paap & Greenberg, 2013), to instead focus on top-down processes which may be more likely shared across domains (including choice behaviors under conditions of free response and error monitoring).

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Appendix A

Data from Excluded Participants

Experiment 1

As shown in the top row of Figure A1, participants who were excluded from analysis because they did not switch often enough in the voluntary conditions appeared to exhibit very large switch costs when they did switch in the voluntary blocks in both linguistic and non-linguistic domains. However, these apparent effects should be interpreted with caution given that many participants contributed no data to switch trials.

Comparisons of included to excluded participants are more stable and meaningful in the single-language and cued language mixing blocks where nearly all participants (95 out of 96) contribute data to all cells. Mixed-effects models were used to compare included to excluded participants for single-language/single-task and mixed-language/mixed-task blocks in each domain. The single-language blocks revealed a significant interaction between participant group and dominance (with a larger dominance effect for excluded participants), $\beta = -130.0$, $SE = 44.5$, $t = -2.92$, and the same interaction was present in the cued mixed-language block, $\beta = -132.1$, $SE = 33.4$, $t = -3.96$. Additional comparisons in the cued mixed-language block revealed that relative to included participants, excluded participants were faster on dominant language trials, $\beta = 85.6$, $SE = 33.0$, $t = 2.60$, and also exhibited marginally smaller cued-switch costs, $\beta = 60.5$, $SE = 32.6$, $t = 1.86$. This latter effect was driven by differences between groups in switch costs in the non-dominant language, $\beta = 104.7$, $SE = 50.4$, $t = 2.08$; no such difference was evident in the dominant language, $\beta =$

20.4, $SE = 36.4$, $t < 1$. No other effects of participant group were significant in the cued mixed-language block or in either the single-task block or cued mixed-task block for read-add trials.

Included and excluded bilinguals in the language task also differed significantly in a number of participant characteristics (see Table 2a) such that those who switched often enough to be included in the analyses reported greater use of Spanish and greater proficiency in Spanish than those who were excluded.

Experiment 2

Visually comparing the top and center rows of Figure A1, as in Experiment 1, excluded participants appeared to exhibit very large switch costs when they did switch in the voluntary blocks in both domains (interpreted again with caution given the sparse data on switch trials for excluded participants in the voluntary block).

Statistical comparisons of included to excluded participants in the single-language and cued-mixing blocks revealed no significant differences with two exceptions, both for cued-add responses: A significant interaction between participant group and trial type, such that included participants exhibited larger switch costs in cued-add responses than excluded participants, $\beta = 49.1$, $SE = 24.8$, $t = 1.98$; and a marginally significant main effect of participant group, such that included participants responded more slowly than excluded participants on cued-add trials, $\beta = 58.9$, $SE = 35.5$, $t = 1.66$.

In addition, unlike in the Experiment 1 picture naming task, there were relatively few significant differences between included and excluded bilinguals in participant characteristics for either task (see Table 2b). Whereas bilinguals in Experiment 1 who chose to switch often enough to be included in the voluntary versus cued comparisons exhibited slower dominant language responses and larger switch costs in cued language switching, these differences were not significant in Experiment 2 (and only the add task produced larger cued-switch costs for included participants).

Experiment 3

Differences between included and excluded participants never reached full significance in any comparison, but there were some trends that resembled comparisons in Experiments 1 and 2. In single-task blocks, included participants were marginally slower than excluded participants in the size-parity tasks, $\beta = 43.2$, $SE = 26.0$, $t = 1.66$; similarly, included participants responded marginally more slowly than excluded participants in the read-add tasks, $\beta = 28.5$, $SE = 17.1$, $t = 1.67$.

In the mixed blocks, included participants tended to exhibit larger switch costs in the parity task, but again this was not a significant effect, $\beta = 31.2$, $SE = 18.5$, $t = 1.69$, and included participants tended to respond more slowly on cued trials, but again not significantly so, $\beta = 51.5$, $SE = 27.1$, $t = 1.90$. All other effects did not approach significance.

Summary

Summarizing these comparisons across all experiments, we found many differences between included and excluded participants without repetition of items in language switching (in Experiment 1). In this case, included bilinguals responded more slowly in their dominant language, exhibited larger cued language switch costs, and reported greater proficiency in Spanish (see Table 2a) than excluded bilinguals. By contrast, read-add tasks revealed no differences between included and excluded participants in Experiment 1, and in Experiments 2 and 3 with repetition of items there were few differences between included and excluded participants in both domains.

Appendix B

Error Rate Data

Experiment 1

Trials were counted as errors when participants either produced an unacceptable response or did not produce a response at all within 3000 ms. All other trials were counted as correct responses (non-errors) except for trials in which the voice key was activated prematurely (e.g., by coughing); such trials were excluded altogether. In the voluntary switching block, error trials on which the participant did not respond were classified as having the same language as the preceding trial (and were thus counted as ‘stay’ trials).⁷

By-participant error rates for each condition are shown in the top row of Figure B1. In the picture naming task, error rates did not appear to suggest speed accuracy tradeoffs. Participants made fewer errors on dominant trials than on non-dominant trials in the single-language blocks (9.4% vs. 23.8%, respectively) and the cued switching block (11.7% vs. 24.3%), but this difference was far smaller and even numerically reversed in the voluntary switching block (9.9% vs. 9.1%), reflecting the pattern of dominance effects in RTs. In addition, the cued switch asymmetry observed in RTs is unlikely to be due to differences in error rates across conditions, as an asymmetry in the same direction was observed in error rates (an increase of 4.9% between stay and switch trials in the dominant language vs. an increase of 3.2% in the non-dominant language). Error rates in the voluntary block reflected smaller or even reversed switch costs (1.4% in the dominant language vs. -4.0% in the non-dominant language). The reversal appears to be due to the relatively low error rate on voluntary non-dominant switch trials (6.9%). This is consistent with the numerically reversed dominance effect in the voluntary switch condition RTs, which is driven by bilinguals’ aversion to switching into the non-dominant language to name difficult pictures (see above).

In the read-add task, participants made about the same number of errors on read and add trials in the single-task blocks (5.7% vs. 5.0%, respectively) and in the cued switching blocks (7.8% vs. 8.3%). However, in the voluntary block, error rates were slightly greater

⁷Alternative classification systems were considered. However, treating errors of omission as a separate category would leave the denominator for the omission error rate calculation undefined; including all voluntary block trials in the denominator for error rate calculations in that block would confound error rates with frequency of occurrence; and excluding them from discussion altogether would draw a false distinction between errors of commission and errors of omission.

for the dominant read task than for the add task (7.4% vs. 4.2%, though note read responses were 292 ms faster than add responses in the RTs). This is similar to the numerically reversed dominance effect in voluntary block error rates for the picture naming task. In contrast to the cued switching RTs and error rates for the picture naming task, which showed larger switch costs for the dominant language than for the non-dominant language, the cued switching error rates showed larger switch costs for the add task than for the read task (5.7% vs. 2.5%, respectively), indicating that the lack of a comparable asymmetry in read-add RTs cannot be explained by differences in error rates.

Experiment 2

By-participant error rates were computed for every condition using the same classification system as in Experiment 1, and are shown in the center row of Figure B1. Collapsing across all conditions, error rates were substantially lower in Experiment 2 than in Experiment 1 for both the picture naming task (1.3% vs. 14.5%, respectively) and the read-add task (2.5% vs. 6.6%). Looking within Experiment 2, error means mirrored the results reported for the RT means. In the cued block of the picture naming task, participants made more errors on switch trials than stay trials (4.7% vs. 1.3%), but this 3.4% switch cost in error rates was about the same for the dominant language as for the non-dominant language (3.7% vs. 3.2%), mirroring the absence of a switch cost asymmetry in RTs. In the cued block of the read-add task, the switch cost in error rates was smaller for the read task than the add task (1.7% vs. 3.3%), consistent with the pattern of RTs. In the voluntary block, error rates were greater for the read task than the add task (5.4% vs. 0.9%). This is the same pattern that was found for the voluntary read-add task in Experiment 1, and the observation of the same pattern in Experiment 2 – which produced much smaller dominance effects than in Experiment 1 – reveals a persistent tradeoff with the read-add task and could affect the interpretation of cost-free switches in the RTs of the read task in the voluntary block of Experiment 2. Importantly, however, error rates for the read task in the voluntary block were about the same for stay trials and switch trials (5.8% and 6.4%, respectively, though the error rate for stay trials in the voluntary block may be inflated due to the error classification system as previously noted), and overall error rates were quite low in Experiment 2.

Experiment 3

By-participant error rates were computed for every condition using the same classification system as in Experiments 1 and 2, and are shown in the bottom row of Figure B1. As in Experiments 1 and 2, the error means generally mirrored the RT means. Collapsing across all conditions, error rates in Experiment 3 were very low for both the size-parity task (2.0%) and the read-add task (1.7%). In the cued block of the size-parity task, participants made 3.6% more errors on switch trials than stay trials (5.0% vs. 1.4%, respectively), but this switch cost in error rates was about the same for the size task as for the parity task (4.0% vs. 3.1%), mirroring the absence of a switch cost asymmetry in RTs. The pattern of error rates for the read-add tasks was the same as in Experiments 1 and 2: The error rate for cued-add switch trials (5.9%) was substantially higher than for all other conditions in the cued block (1.3% to 2.7%), leading to larger switch costs for the cued-add task than the cued-read task (3.4% vs. 1.4%), and error rates in the voluntary block were greater for the read task than the add task (3.3% vs. 0.7%, though read responses were 55 ms faster than add responses in the

RTs). It is not clear why the read task elicited slightly more errors but faster response times than the add task in the voluntary block, but the appearance of this pattern without and with repetition in bilinguals (Experiments 1 and 2), and in monolinguals (in Experiment 3), demonstrates this finding as a consistent idiosyncratic property of switching between the read and add tasks.

Figure 1. Experiment 1–3 naming latencies (in milliseconds) from included participants as a function of domain/task-set (picture naming, read-add, size-parity), instruction type (cued, voluntary), dominance (dominant language/task non-dominant language/task), and trial type (single, stay, switch). Means are shown separately for the picture naming task (left column), read-add task (center column), and size-parity task (right column); and for non-repeated items (Experiment 1 bilinguals, top row) and repeated items (Experiment 2 bilinguals, center

row; and Experiment 3 monolinguals, bottom row). Not all tasks were conducted in every experiment; blank spaces denote untested combinations. Error bars show standard errors.

Figure 2.

Correlations between intrusion rates (i.e., the proportion of trials on which bilinguals did not complete the task indicated by the cue) in the cued conditions of Experiment 1 (panel a) and Experiments 2 (panel b), and between switch rates (i.e., the proportion of trials on which bilinguals chose to switch tasks) in the voluntary conditions of Experiment 1 (panel c) and Experiment 2 (panel d). Data points are weighted such that the area of each point scales linearly with the number of observations it represents. For example, a point representing five bilinguals has an area five times that of a point representing a single bilingual.

Figure 3. Naming latencies (in milliseconds) in each condition for bottom-upper ($n=17$) and top-downer ($n=20$) bilinguals tested in Experiment 2. Error bars show standard errors.

Figure A1. Experiment 1–3 naming latencies (in milliseconds) from excluded participants as a function of domain/task-set (picture naming, read-add, size-parity), instruction type (cued, voluntary), dominance (dominant language/task non-dominant language/task), and trial type (single, stay, switch). Not all tasks were conducted in every experiment; blank spaces denote untested combinations. Error bars show standard errors.

Figure B1.

Experiment 1–3 error rates from included participants as a function of domain/task-set (picture naming, read-add, size-parity), instruction type (cued, voluntary), dominance (dominant language/task non-dominant language/task), and trial type (single, stay, switch). Not all tasks were conducted in every experiment; blank spaces denote untested combinations. Error bars show standard errors.

Table 1

Design and task details for Experiments 1–3.

Experiment	Participants	Repetition of Stimuli	Tasks	Stimuli	Sample Stimulus	Dominant Response	Non-Dominant Response
Experiment 1	Bilinguals	No	Picture Naming	Pictures		Dominant language ("tree")	Non-dominant language ("árbol")
			Read-Add	2- to 4-digit numbers	34	Read task ("thirty-four")	Add task ("seven")
Experiment 2	Bilinguals	Yes	Picture Naming	Pictures		Dominant language ("tree")	Non-dominant language ("árbol")
			Read-Add	2- to 4-digit numbers	34	Read task ("thirty-four")	Add task ("seven")
Experiment 3	Monolinguals	Yes	Size-Parity	1-digit numbers	7	Size task ("bigger")	Parity task ("odd")
			Read-Add	2- to 4-digit numbers	34	Read task ("thirty-four")	Add task ("seven")

Table 2

Characteristics of included and excluded participants in Experiments 1–3.

	(a) Experiment 1									
	Picture Naming					Read-Add				
	Included (n=68)		Excluded (n=28)			Included (n=86)		Excluded (n=10)		
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	
Age	21.2	2.5	19.8	1.6	**	20.8	2.4	21.2	1.7	
Age of acquisition of English	4.9	3.6	3.3	2.9	*	4.8	3.4	1.5	2.2	**
Age of acquisition of Spanish	0.3	0.9	1.1	2.5	*	0.6	1.6	0.1	0.2	
English speaking ability ^a	6.5	0.8	6.4	0.9		6.4	0.9	6.8	0.4	
English writing ability ^a	6.4	0.9	6.2	0.9		6.3	0.9	6.5	0.8	
English listening ability ^a	6.5	1.1	6.5	0.7		6.5	1.0	6.7	0.7	
English reading ability ^a	6.5	0.7	6.4	0.8		6.5	0.8	6.6	0.7	
Spanish speaking ability ^a	6.0	1.3	5.6	1.3		5.9	1.3	6.0	1.3	
Spanish writing ability ^a	5.5	1.2	4.7	1.4	**	5.3	1.3	5.1	1.4	
Spanish listening ability ^a	6.4	1.0	6.0	1.1	†	6.3	1.0	6.4	1.2	
Spanish reading ability ^a	6.0	1.0	5.4	1.4	*	5.8	1.1	5.6	1.3	
Percent English use currently	72.4	20.4	83.9	15.3	**	74.9	19.9	83.3	16.1	
Percent English use during childhood	49.3	21.2	60.6	21.2	*	51.1	21.9	65.3	18.8	†
Switching frequency currently ^b	3.0	1.2	3.1	1.5		3.1	1.3	2.8	1.7	
Switching frequency in childhood ^b	2.8	1.5	3.2	1.4		2.9	1.5	3.1	1.7	
Matrix reasoning test	35.3	5.9	33.5	5.9		34.6	6.1	35.9	4.7	
Shipley vocabulary test	29.2	3.1	28.9	3.3		28.9	3.0	30.4	4.1	

(b)
Experiment 2

	Picture Naming				Read-Add			
	Included (n=37)		Excluded (n=31)		Included (n=44)		Excluded (n=24)	
	M	SD	M	SD	M	SD	M	SD
Age	21.3	3.1	20.2	1.7	21.0	3.0	20.5	1.8
Age of acquisition of English	4.2	2.5	3.7	2.9	3.9	2.7	4.1	2.6
Age of acquisition of Spanish	0.3	1.2	0.2	0.5	0.3	1.1	0.3	0.5
English speaking ability ^a	6.2	0.9	6.3	0.9	6.3	0.8	6.3	1.0
English writing ability ^a	6.2	0.9	6.1	1.0	6.2	1.0	6.2	0.8
English listening ability ^a	6.5	0.8	6.4	1.0	6.5	0.7	6.4	1.1
English reading ability ^a	6.4	0.8	6.4	0.9	6.4	0.8	6.4	0.9
Spanish speaking ability ^a	6.1	1.1	5.8	1.3	6.0	1.1	5.9	1.5
Spanish writing ability ^a	5.4	1.3	4.9	1.2	5.2	1.3	5.1	1.2
Spanish listening ability ^a	6.3	1.0	6.1	1.3	6.3	1.0	6.0	1.4
Spanish reading ability ^a	5.9	1.3	5.5	1.1	5.7	1.2	5.6	1.2
Percent English use currently	76.7	18.6	81.3	14.1	77.8	18.5	80.5	13.0
Percent English use during childhood	50.9	21.7	57.1	17.0	52.1	22.1	56.7	14.7
Switching frequency currently ^b	3.1	1.3	3.5	1.2	3.1	1.3	3.5	1.1
Switching frequency in childhood ^b	3.1	1.4	3.6	1.4	3.2	1.4	3.6	1.3
Matrix reasoning test	32.8	5.6	35.1	4.6	32.9	5.6	35.9	3.9
Shipley vocabulary test	28.2	3.4	27.4	2.7	27.4	3.2	28.7	2.6

(c)
Experiment 3

	Size-Parity				Read-Add			
	Included (n=60)		Excluded (n=44)		Included (n=57)		Excluded (n=47)	
	M	SD	M	SD	M	SD	M	SD
Age	20.8	2.6	21.7	6.7	20.8	2.6	21.6	6.5
Age of acquisition of English	0.2	0.9	0.7	1.6	0.2	0.9	0.6	1.6
Age of exposure to other language	12.0	3.6	11.9	4.2	11.9	3.8	12.1	3.9

(c) Experiment 3									
	Size-Parity				Read-Add				
	Included (n=60)		Excluded (n=44)		Included (n=57)		Excluded (n=47)		
	M	SD	M	SD	M	SD	M	SD	
English speaking ability ^a	7.0	—	7.0	0.2	7.0	0.1	7.0	—	
English writing ability ^a	7.0	0.2	7.0	0.3	7.0	0.3	7.0	—	
English listening ability ^a	7.0	—	7.0	—	6.9	0.3	7.0	—	
English reading ability ^a	7.0	0.2	7.0	0.3	6.9	—	7.0	—	
Other speaking ability ^a	2.7	1.4	2.5	1.1	2.8	1.3	2.7	1.0	
Other writing ability ^a	2.6	1.4	2.3	1.2	2.7	1.3	2.4	1.1	
Other listening ability ^a	3.1	1.6	3.0	1.3	3.3	1.4	3.2	1.2	
Other reading ability ^a	3.0	1.4	2.8	1.4	3.1	1.3	3.0	1.3	
Percent English use currently	98.4	4.0	99.7	1.0	*	98.4	4.0	99.6	
Percent English use during childhood	97.5	4.0	97.1	3.1		97.6	4.0	97.0	
Switching frequency currently ^b	1.3	1.3	1.3	1.5		1.3	1.3	1.2	
Switching frequency in childhood ^b	1.0	1.0	1.2	1.3		1.0	1.1	1.3	
** <i>p</i> <.01;									
* <i>p</i> <.05;									
† <i>p</i> <.10									
^a Ratings were on a scale from 1 (little to no knowledge) to 7 (like a native speaker).									
^b The 6-point rating scale included the following anchors: 1 (never), 2 (very infrequently), 3 (occasionally), and 6 (constantly).									
** <i>p</i> <.01;									
* <i>p</i> <.05;									
† <i>p</i> <.10									
** <i>p</i> <.01;									
* <i>p</i> <.05;									
† <i>p</i> <.10									

Table 3
Experiment 1 single-language and single-task block results and effect sizes derived from mixed-effects models.

	Picture Naming			Read-Add			Cross-Domain		
	Estimate	SE	t	Estimate	SE	t	Estimate	SE	t
Intercept	1133.9	20.1	56.33 *	960.4	18.5	51.91 *	1026.9	15.0	68.53 *
Domain							-189.0	23.7	-7.97 *
Dominance	216.8	24.1	9.01 *	414.9	26.9	15.42 *	341.0	18.4	18.49 *
Dominance * Domain							181.2	37.4	4.84 *

* $p < .05$

Table 4
Experiment 1 mixed-language and mixed-task block results and effect sizes derived from mixed-effects models.

	Picture Naming			Read-Add			Cross-Domain		
	Estimate	SE	t	Estimate	SE	t	Estimate	SE	t
Intercept	1252.2	19.8	63.19*	1094.7	20.6	53.21*	1153.9	16.0	72.24*
Domain							-164.0	23.7	-6.93*
Trial Type	97.7	10.8	9.05*	68.7	7.7	8.94*	79.3	6.5	12.16*
Trial * Domain							-31.0	13.2	-2.35*
Dominance	52.0	14.9	3.49*	349.1	25.0	13.99*	231.0	15.4	14.96*
Dominance * Domain							282.6	29.3	9.64*
Instruction Type	-9.9	14.2	-0.70	-88.5	13.5	-6.57*	-55.0	10.0	-5.48*
Instruction * Domain							-83.8	18.5	-4.52*
Trial * Dominance	-71.4	23.2	-3.08*	8.4	16.9	0.50	-24.7	14.1	-1.75†
Trial * Dominance * Domain							78.4	27.6	2.84*
Trial * Instruction	-28.8	22.8	-1.26	-11.0	18.5	-0.60	-17.7	15.7	-1.13
Trial * Instruction * Domain							9.0	24.0	0.38
Dominance * Instruction	-140.5	23.3	-6.03*	-88.2	18.6	-4.75*	-105.0	14.1	-7.45*
Dominance * Instruction * Domain							48.2	29.5	1.64
Trial * Dominance * Instruction	32.8	43.1	0.76	71.3	33.6	2.12*	49.1	27.5	1.78†
Trial * Dominance * Instruction * Domain							56.0	49.1	1.14

* $p < .05$;

† $p < .10$

Table 5
Experiment 2 single-language and single-task block results and effect sizes derived from mixed-effects models.

	Picture Naming			Read-Add			Cross-Domain		
	Estimate	SE	t	Estimate	SE	t	Estimate	SE	t
Intercept	792.3	16.7	47.33*	730.6	29.4	24.88*	755.8	18.3	41.41*
Domain							-57.3	29.5	-1.95 [†]
Dominance	54.5	18.9	2.89*	99.4	38.7	2.57*	78.9	21.6	3.66*
Dominance * Domain							45.4	43.3	1.05

* $p < .05$;
[†] $p < .10$

Table 6
Experiment 2 mixed-language and mixed-task block results and effect sizes derived from mixed-effects models.

	Picture Naming			Read-Add			Cross-Domain		
	Estimate	SE	t	Estimate	SE	t	Estimate	SE	t
Intercept	805.0	19.5	41.19*	814.5	31.3	26.04*	799.3	20.3	39.30*
Domain							17.7	29.1	0.61
Trial Type	72.7	11.4	6.41*	44.2	11.0	4.00*	58.4	8.2	7.11*
Trial * Domain							-28.6	13.1	-2.18*
Dominance	2.8	10.7	0.26	103.5	19.8	5.22*	58.3	11.2	5.22*
Dominance * Domain							103.4	22.4	4.61*
Instruction Type	-35.9	15.2	-2.35*	-66.7	15.4	-4.33*	-55.8	12.0	-4.67*
Instruction * Domain							-19.7	18.3	-1.07
Trial * Dominance	4.2	15.4	0.27	65.8	16.3	4.03*	32.1	11.0	2.93*
Trial * Dominance * Domain							59.6	21.6	2.76*
Trial * Instruction	-49.2	29.2	-1.69 [†]	-31.7	14.9	-2.13*	-35.7	15.9	-2.25*
Trial * Instruction * Domain							27.5	26.8	1.02
Dominance * Instruction	-2.8	17.0	-0.17	-3.0	29.5	-0.10	-2.7	16.6	-0.16
Dominance * Instruction * Domain							2.4	31.7	0.08
Trial * Dominance * Instruction	1.9	24.8	0.08	-21.3	40.2	-0.53	-13.9	16.9	-0.82
Trial * Dominance * Instruction * Domain							-33.6	33.9	-0.99

* $p < .05$;

[†] $p < .10$

Table 7

Pearson bivariate correlations between linguistic and non-linguistic switch costs in Experiment 1 (top panel) and Experiment 2 (bottom panel).

Without Repetition (Experiment 1)						
Cued			Voluntary			
	Dominant	Read	Non-Dominant	Add	Dominant	Read Non-Dominant
Cued						
Read	0.15					
Non-Dominant	-0.04 ^a	-0.08				
Add	-0.09	-0.04 ^b	0.01			
Voluntary						
Dominant	-0.07 ^a	-0.04	0.04 ^a	-0.08		
Read	0.22 [†]	-0.09 ^b	-0.17	-0.17 ^b	0.11	
Non-Dominant	-0.13 ^a	-0.26 [*]	0.00 ^a	0.07	0.02 ^a	-0.15
Add	-0.21 [†]	-0.17 ^b	-0.01	-0.14 ^b	0.07	0.15 ^b 0.28 [*]
With Repetition (Experiment 2)						
Cued			Voluntary			
	Dominant	Read	Non-Dominant	Add	Dominant	Read Non-Dominant
Cued						
Read	0.15 ^b					
Non-Dominant	0.12 ^a	-0.22				
Add	0.67 ^{**}	0.27 ^{b†}	0.01			
Voluntary						
Dominant	-0.17 ^a	0.28	0.14 ^a	-0.02		
Read	0.18	0.50 ^{b**}	0.17	0.20 ^b	0.49 ^{**}	
Non-Dominant	-0.21 ^a	0.15	0.03 ^a	0.09	0.30 ^{b†}	0.30
Add	0.09	0.17 ^b	-0.06	0.06 ^b	0.38 [*]	0.42 ^{b**} 0.22

** $p < .01$;
* $p < .05$;
† $p < .10$
a $n = 68$ instead of 62
b $n = 86$ instead of 62
** $p < .01$;
* $p < .05$;
† $p < .10$

Table 8

Means (and standard deviations) for bilinguals who used bottom-up and top-down strategies in the Experiment 2 read-add task (see Figure 3 for analogous means in language task).

	Bottom-Uppers					Top-Downers				
	Stay		Switch		Switch Cost	Stay		Switch		Switch Cost
	M	SD	M	SD		M	SD	M	SD	
Voluntary										
Read	683	100	691	88	8	751	135	752	174	1
Add	830	143	912	91	82	823	123	901	219	78
Cued										
Read	756	99	801	162	46	802	170	811	191	10
Add	873	147	978	208	106	872	143	966	199	94

Table 9

Experiment 3 single-task block results and effect sizes derived from mixed-effects models.

	Size-Parity			Read-Add			Cross-Task Set		
	Estimate	SE	t	Estimate	SE	t	Estimate	SE	t
Intercept	602.5	11.1	54.09*	629.6	18.8	33.50*	613.2	12.1	50.81*
Task Set							24.5	18.1	1.35
Dominance	49.1	11.1	4.43*	94.3	27.6	3.42*	71.0	14.4	4.94*
Dominance * Task Set							44.4	30.1	1.47

* $p < .05$;
† $p < .10$

Table 10

Experiment 3 mixed-task block results and effect sizes derived from mixed-effects models.

	Size-Parity			Read-Add			Cross-Task Set		
	Estimate	SE	t	Estimate	SE	t	Estimate	SE	t
Intercept	729.6	16.3	44.78*	698.1	22.4	31.15*	710.1	16.1	44.00*
Task Set							-32.5	19.9	-1.64
Trial Type	56.2	7.4	7.61*	31.8	7.9	4.01*	43.6	5.7	7.67*
Trial * Task Set							-24.9	10.2	-2.45*
Dominance	47.0	12.9	3.65*	63.2	15.6	4.06*	55.5	10.3	5.39*
Dominance * Task Set							16.1	19.6	0.82
Instruction Type	-32.7	9.8	-3.33*	-71.1	13.1	-5.44*	-49.3	8.8	-5.58*
Instruction * Task Set							-37.2	13.7	-2.72*
Trial * Dominance	6.8	12.7	0.53	9.2	11.6	0.79	8.1	8.9	0.91
Trial * Dominance * Task Set							3.6	14.9	0.24
Trial * Instruction	-54.0	14.9	-3.62*	0.6	16.5	0.04	-24.6	11.5	-2.13*
Trial * Instruction * Task Set							52.4	21.6	2.42*
Dominance * Instruction	-18.6	15.1	-1.23	-12.7	22.3	-0.57	-13.4	13.0	-1.03
Dominance * Instruction * Task Set							3.1	24.0	0.13
Trial * Dominance * Instruction	-13.0	31.6	-0.41	-11.5	24.6	-0.47	-11.4	13.1	-0.87
Trial * Dominance * Instruction * Task Set							1.1	26.2	0.04

* $p < .05$;† $p < .10$