THE BILINGUAL ADVANTAGE IN SWITCHING: ARE TWO BETTER THAN ONE?

A Dissertation

Presented to

The Faculty of the Department

of Psychology

University of Houston

In Partial Fulfillment

Of the Requirements for the Degree of

Doctor of Philosophy

By

Maya R. Greene

December, 2015

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Abstract

Most previous studies of the bilingual advantage analyzed speed and accuracy results from the same task separately. Using this method, some found advantages in switching tasks that favor bilinguals while others have not, and there is ongoing controversy regarding the existence of the bilingual advantage. The present study sought to examine the bilingual advantage in non-verbal switching using a novel multilevel structural equations modeling (ML-SEM) framework that incorporated both reaction time and accuracy in order to assess the trial level and person level relationship between these variables. In addition, the roles of parental education level (PED) and language proficiency were examined. The results of this model did not indicate the existence of a bilingual advantage, and there were no significant correlations between reaction time and accuracy at the person level or at the trial level. The lack of significant correlation may be due to high overall accuracy in the task. English proficiency was a significant predictor of reaction time in both bilinguals and monolinguals, such that higher proficiency was related to faster responses. In the monolinguals, higher English proficiency was also related to more accurate performance, a relationship that was non-existent in the bilinguals. In the bilinguals, Spanish proficiency was a significant predictor of reaction time, such that higher proficiency was associated with slower responses. This finding, along with the significance of English proficiency as a predictor of performance in both groups, calls into question the non-verbal nature of this task. No significant effect of PED was found. This study showcases a novel methodology that may encourage future researchers to examine both reaction time and accuracy together, suggests that bilingualism may serve to specifically tune accuracy, and highlights the importance of considering language background variables even when using tasks that are not explicitly verbal in nature.

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What are Cognitive Control and the Theory Behind the Bilingual Advantage?

The 2011 American Community Survey revealed that more than 40 million bilinguals currently reside in the United States. Given this fact, increased attention must be paid to understanding how bilingualism affects the brain. Cognitive control, sometimes referred to as executive functions (Hernandez, 2013), is a set of complex general mechanisms that oversee various cognitive functions. In a seminal paper, Miyake et al. (2000) examined the mechanism of executive functions, and found that they can be divided into three correlated but dissociable components. Shifting between mental sets is defined as the subcomponent of executive function that mediates switching between tasks. The subcomponent of updating and monitoring is closely linked with working memory function: the role of this subcomponent is to monitor incoming information and update task demands by replacing old irrelevant information in working memory with new data. Inhibition, the final subcomponent, is concerned with the suppression of a predominant response. These subcomponents are all correlated with one another, indicating that they are all involved to some extent in various cognitive control tasks. The dynamic nature of executive functions lends itself to the idea of training: could constant utilization of these control mechanisms lead to their enhancement?

Perhaps the most widely recognized form of cognitive control training is the notion of the bilingual advantage. Pioneered by Ellen Bialystok, the bilingual advantage theory suggests that bilinguals' constant management of their two languages engages and enhances their cognitive control mechanisms, and therefore leads to superior cognitive control performance compared to monolinguals even on tasks that are not explicitly linguistic in nature (Abutalebi et al., 2012; Barac & Bialystok, 2012; Bialystok, 1999, 2006; Bialystok, Craik, & Luk, 2008; Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok, Craik, & Ryan, 2006; Bialystok & Martin, 2004; Bialystok, Martin, & Viswanathan, 2005; Bialystok & Viswanathan, 2009; Carlson & Meltzoff, 2008; Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Costa, Hernandez, & Sebastian-Galles, 2008; Emmorey, Luk, Pyers, & Bialystok, 2008; Garbin et al., 2010; Gold, Kim, Johnson, Kryscio, & Smith, 2013; Hernández, Martin, Barceló, & Costa, 2013; Kovács & Mehler, 2009; Poarch & van Hell, 2012; Yang, Yang, & Lust, 2011; Yoshida, Tran, Benitez, & Kuwabara, 2011). While most of the early research focused on investigating the bilingual advantage in inhibition, recent studies have examined the effects of bilingualism on switching tasks, which is related to another subcomponent described by Miyake et al. (2000), shifting of mental sets.

The Bilingual Advantage in Switching: Are Two Better Than One?

In recent years, a number of studies investigated task-switching in bilinguals and monolinguals (Barac & Bialystok, 2012; Garbin et al., 2010; Gold et al., 2013; Hernández et al., 2013; Mor, Yitzhaki-Amsalem, & Prior, 2014; Paap & Greenberg, 2013; Paap, Johnson, & Sawi, 2014; Paap & Sawi, 2014; Prior & Gollan, 2011; Prior & MacWhinney, 2010). While some researchers report bilingual advantages, others do not, and the presence of a bilingual advantage in task-switching is a highly contentious subject.

In one of the first studies to examine bilingualism's relationship with switching, Prior and MacWhinney (2010) examined the performance of bilinguals and monolinguals in a shape-color rule-switching task. Forty-four bilinguals and 44 monolinguals completed a task in which they had to alternate between responding to the shape of the stimulus or to the color of the stimulus, with the rule determined by a cue. In the mixed-task blocks, participants had to switch between rules, and were presented with 72 switch trials and 72 non-switch trials over three blocks. Each stimulus presentation that required a response was preceded by a cue that indicated whether the participant was supposed to respond to the shape or to the color of the stimulus. Whether a given trial was a switch or non-switch depended on the preceding trial. Switching costs—the difference in reaction time (RT) and accuracy between switch and non-switch trials—were analyzed for bilinguals and monolinguals. A two-way ANOVA revealed a main effect of condition for both accuracy and RT, where responses to non-switch trials were both faster and more accurate than responses to switch trials. The interaction between language group (bilingual or monolingual) and condition was significant for RT but not for accuracy. Bilinguals demonstrated faster RTs to the switch trials compared to monolinguals, while responses to non-switch trials were similar for the two groups (Table 1). Prior and MacWhinney concluded that bilinguals exhibited smaller switching costs compared to monolinguals—the bilingual advantage in task-switching.

While Prior and MacWhinney found a bilingual advantage in reaction time but not accuracy, other researchers do report a bilingual advantage in accuracy. Garbin et al. (2010) administered a shape-color switching task to 21 monolinguals and 19 bilinguals. Over the course of two runs, participants performed 60 switch and 60 non-switch trials in which they had to either respond to the color (red or blue) or to the shape (circle or square) of a stimulus. Using an ANOVA to examine the effects of language group (bilingual or monolingual) and condition (switch or non-switch), they found a significant interaction between language group and condition in accuracy and a similar one in RT that was marginally significant ($p=.051$). These results parallel findings from Prior and MacWhinney (2010) and indicate that bilinguals enjoy an advantage in the form of decreased switching costs compared to monolinguals (Figure 1). Taken together, these studies suggest a task-switching advantage for bilinguals.

Studies of task switching are relatively few compared to studies examining inhibitory control (e.g. Simon task, flanker task); however, even in this relatively limited literature base, there is controversy regarding the existence of a bilingual advantage. Paap and Greenberg (2013) administered a wide variety of cognitive tasks to bilinguals and monolinguals, among which was a shape-color switching task. A total of 122 bilingual participants and 151 monolingual participants were recruited across three studies. Switching costs were analyzed using ANOVA. The researchers reported no significant differences between bilinguals and monolinguals in either RT or accuracy, and in fact, report a trend in RT towards a bilingual *disadvantage*. Follow up studies also failed to find a bilingual advantage in switching costs (Paap et al., 2014; Paap & Sawi, 2014). Given the relatively few studies of task-switching and the mixed results it is necessary to continue to examine whether or not bilingual advantages in switching exist.

The Role of Individual Differences

Individual differences, specifically in language use, proficiency, and socioeconomic status, have been previously shown to be related to the performance of executive function tasks. Prior and Gollan (2011) administered a shape-color task to 47 monolinguals, 41 Spanish-English bilinguals, and 43 Mandarin-English bilinguals. The goal of this study was to examine whether patterns of daily language use were related to performance on this task. Spanish-English bilinguals reported switching between their two languages more on a daily basis than did the Mandarin-English bilinguals. Using an ANOVA, Prior and Gollan found a main effect of condition, where responses to the non-switch trials were faster than to the switch trials. Somewhat unexpectedly, they found that Spanish-English bilinguals responded more slowly than both the Mandarin-English bilinguals and the monolinguals. The condition by group interaction was not significant. Prior and Gollan note that the Spanish-English bilinguals reported lower parental education levels (PED), and that this difference may affect their performance on the task. They reasoned that given their disadvantaged background it is actually surprising that the Spanish-English bilinguals did not exhibit worse performance in terms of increased switching-costs. Follow up ANCOVA analysis with relative switching scores (where the switch cost was divided by mean RT on non-switch trials) and including PED as a covariate, revealed that Spanish-English bilinguals presented with smaller switching costs compared to the monolinguals and the Mandarin-English bilinguals. Monolinguals and Mandarin-English bilinguals did not differ from one another.

The study by Prior and Gollan serves to highlight the importance of individual differences variables that may influence performance in the shape-color task. First, the pattern of daily language use was identified as an important factor since Spanish-English bilinguals presented with smaller switching costs compared to monolinguals but Mandarin-English bilinguals did not. Second, this effect could only be discovered once parental education level was controlled for. In considering the raw scores, Spanish-English bilinguals performed significantly slower than the other two groups.

Other studies, mostly conducted with children, have additionally discovered that individual differences in variables such as PED (or socioeconomic status) and language proficiency have an effect on task performance. Iluz-Cohen and Armon-Lotem (2013) found that bilingual children with higher language proficiency outperform those with lower proficiency in tasks of executive function. Morton and Harper (2007) found that bilingual and monolingual children who were matched on socioeconomic background did not differ in their performance on the Simon task, but children with high socioeconomic status performed better than children from more disadvantaged backgrounds. Socioeconomic status (which is assessed in part by parental education level) has also been shown in other studies to be related to cognitive function and academic performance (Caldas & Bankston, 1997; Mezzacappa, 2004; Sarsour et al., 2011). These findings add to a growing literature that suggests that parental education level/socioeconomic status and language proficiency/use should be taken into consideration whenever cognitive functions are being examined, even if the tasks used are not explicitly verbal.

Speed and Accuracy: Beyond ANOVAs

Regardless of whether or not these reviewed studies report a bilingual advantage, they all are consistent in the way in which their results were attained; every single one of these studies analyzed reaction time and accuracy separately. Most of these studies presumably utilized separate ANOVAs to investigate the effects of condition (switch or non-switch) and language status (bilingual or monolingual) on reaction time and accuracy. To this day, to my knowledge, not a single published study of the bilingual advantage in task-switching considered the relationship between speed and accuracy. This is in spite of a long line of research that suggests a relationship between these two factors (Fitts, 1966; Forstmann et al., 2011; Giordano, McElree, & Carrasco, 2004; Ivanoff, Branning, & Marois, 2008; Liu & Watanabe, 2012; Pachella & Pew, 1968; Wickelgren, 1977). Despite the well-known connection between reaction time and accuracy, the majority of studies today consider these two variables separately, mostly utilizing ANOVAs. This disconnect is likely due to the complexity of models designed to examine this relationship.

The relationship between reaction time and accuracy has been known and investigated for many years, with researchers discovering that emphasis on accuracy led to greater reaction times and decreased errors, while emphasis on speed decreased reaction time and increased errors (Fitts, 1966; Forstmann et al., 2011; Pachella & Pew, 1968). This relationship is presumably also present in task switching. In the context of bilingualism, it is possible that a bilingual advantage may be present in the form of decreased speed-accuracy tradeoffs. Bilinguals' need to constantly manage their two languages and make accurate responses (i.e. use the correct language), may lead to lesser speed-accuracy tradeoffs than in monolinguals. In other words, bilinguals must be accurate, regardless of how quickly they respond. This may lead to a decrease in the relationship between reaction time and accuracy in bilinguals compared to monolinguals. This idea cannot be tested with the traditional approaches used by the field, since it requires the joint examination of both reaction time and accuracy. The joint modeling of reaction time and accuracy has been attempted in the past (though never in the context of the bilingual advantage), however the approach is not widespread.

The disconnect between advanced modeling options which allow for the examination of novel and exciting hypotheses and actual data analysis is likely due to the complexity of these models and inappropriateness for data derived from cognitive tasks. Vandekerckhove et al. (2011) for example, advocate for the use of the hierarchical diffusion model to examine individual differences in response time in two choice tasks. However, this model is complex and difficult to apply and is unlikely to be widely adopted by the general research community. Given that one of the main objectives for this examination is to propose a practical way to analyze speed-accuracy tradeoffs that can be easily applied by most researchers, this model is not appropriate for this study. Fox, Entink, and van der Linden (2007) present an approach to examine speed and accuracy tradeoff using a combination of Item Response Theory (IRT) model for the responses and a lognormal model for the reaction time. The major caveat in Fox et al.'s method is that the relationship between speed and accuracy at the individual trial level is not considered; this relationship is only examined at the person level. This model, if applied to cognitive task data, would therefore provide an incomplete picture: the repeated-measures nature of this data (several trials of the same condition) allows for examining trial-level and person-level tradeoffs. For example, in the shape-color task, it is possible that the tradeoff in individual trials is such that lower reaction times are associated with a greater probability of an incorrect response. The magnitude of this association may also be different for switch and non-switch conditions. At the person level, the relationship may not necessarily be the same. Even though at the trial level this relationship is hypothesized to be positive (higher reaction time—slower responses—associated with more accurate responses), at the person level this relationship may be negative (people who are faster are also more accurate). Applying Fox et al's model to this type of data, and only examining person-level relationships, would therefore leave many interesting questions unaddressed.

A final modeling approach, presented recently, may prove promising for examining speed-accuracy tradeoffs in cognitive task data. Molenaar, Tuerlinckx, and van der Mass (2015), introduce bivariate generalized linear item response theory models (B-GLIRT) for use in the modeling of reaction time and bivariate responses (e.g. accuracy). This model relies on latent traits. A latent trait is the unobserved quality that the test administered is attempting to measure. For example, in studies of task switching, we are attempting to measure the unobservable construct “switching” by administering a test such as the shape-color task. Performance on individual trials are observed indicators of that latent trait. In the B-GLIRT model, the responses and speed are used as observed indicators loading on two separate latent variables, one for the latent ability trait[1] θ_p and one for speed τ_p, respectively, where p stands for person. A relationship is then specified between the latent variables θ_p and τ_p, called the cross-relation function (*f*(.)). The nature of the cross-relation function depends on the goal of the researcher. Because Molenaar and colleagues treat the responses as indicators of the latent trait and not the reaction time, in their model the accuracy θ_p latent variable accounts for any shared variance between speed and accuracy. This way, τ_p is the unique speed variance in the responses with all information about accuracy, both shared and unique, reflected by θ_p. Molenaar et al. are not necessarily concerned with the speed-accuracy tradeoff, but rather with presenting accuracy in the most complete way. Even though the goals of Molenaar et al. are not the same as those in the present examination, the conceptualization of repeated trials as indicators of latent traits and the attention given to the relationship between them is the first step in understanding speed-accuracy tradeoffs in cognitive tasks.

Taken together, these studies bring to light a number of issues regarding the bilingual advantage. First, many studies have shown that bilinguals may perform cognitive tasks

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[1] Molenaar et al. adopt the point of view that the responses (not the reaction time) indicate the latent trait. This likely arose from the Item Response Theory approach, in which responses to items of a scale are used to define the underlying construct (e.g. depression). In their terminology therefore, the responses are the indicators of the latent trait, whereas the reaction time is considered to be reflective of a general speed variable. This is not the case in examinations of the bilingual advantage, in which both speed and accuracy are considered indicators of the underlying ability.

differently or more efficiently, but there are inconsistencies in these findings. Second, background variables (e.g. parental education level and language proficiency) may influence cognitive control abilities and should be taken into account in bilingual advantage examinations. Finally, there is a fundamental lack of understanding of speed-accuracy tradeoffs in cognitive tasks in bilinguals and monolinguals. It is possible that the bilingual advantage is best demonstrated in decreased speed-accuracy tradeoffs, and not in just one or the other. Taking into account the immense interest in bilingualism's effects on the brain, demonstrated through the plethora of both academic and non-academic articles on the topic, it is surprising that this last point has not been addressed. The aim of this examination was to investigate this unknown relationship between speed and accuracy in switching in bilinguals and monolinguals, and provide a more complete view of how bilingualism affects the brain and behavior.

The Present Study

The present study consisted of two experiments. Experiment 1 examined the relationship between reaction time and accuracy in bilinguals and monolinguals and sought to demonstrate the use of a powerful new modeling technique. Experiment 2 explored the role language proficiency and parental education level may play in predicting reaction time and accuracy in a non-verbal switching task. In experiment 1 reaction times and accuracy from a shape-color task administered to bilinguals and monolinguals were first modeled using modified B-GLIRT models (Figures 2 and 3, respectively), with some modifications made to follow-up models based on initial model results. In experiment 2, language proficiency and parental education level were added to the model to examine their effect in each group.

Four hypotheses were tested in experiment 1. The first two focused on the correlation between reaction time and accuracy at the trial and person level. The last two hypotheses considered parameters across groups. Although none of the proposed hypotheses from experiment 1 were supported, it is my hope that the availability of this methodology would encourage future studies to use more difficult tasks that were previously avoided due to the need to examine reaction time and accuracy separately. The original hypotheses tested were:

1. There would be a positive relationship between accuracy and reaction time at the individual trial level (labeled "a" and "b" in Figure 2, and a' and b' in Figure 3). It is predicted that individual responses that are faster, would be more likely to be incorrect. As reaction time increases, trials are more likely to be correct. This was predicted to be the same for both switch ("a") and non-switch ("b") conditions.
2. There would be a negative relationship between general accuracy and reaction time (labeled "c" and c' in Figures 2 and 3). In other words, individuals who are faster in general are more likely to display more accurate responses. This hypothesis stems from the notion that reaction time and accuracy both reflect a single ability, and that individuals high on this ability will be faster and more accurate than individuals who have low ability.
3. The ratio of factor loadings (d / e in Figure 2) will be closer to 1 in bilinguals than in monolinguals (d' / e' in Figure 3), indicating that the switch and non-switch reaction times are more similar to one another in the bilinguals. A similar pattern was expected for accuracy (f / g and f' / g'). This is akin to finding larger "switch costs" for monolinguals than bilinguals.

4. There will be smaller speed-accuracy tradeoffs in bilinguals than in monolinguals at the trial level, such that the correlations would be weaker. In other words, it is expected that a' will be greater than a, and b' will be greater than b. Based on previous literature suggesting superior cognitive control skills in bilinguals, it is expected that an advantage will be discovered in the form of a smaller speed-accuracy tradeoff for bilinguals. This hypothesis has two sub-components. It is possible that this decrease in speed-accuracy tradeoff will occur in both the switching ("a") and non-switching ("b") conditions, indicating a general cognitive control advantage for bilinguals. Alternatively, and more in line with previous findings, this decrease may be present in the switching condition only, suggesting a specific advantage for bilinguals in switching.

In experiment 2, the effects of parental education level (PED) and language proficiency were examined in both groups. Although no specific hypotheses were initially listed, based on previous literature (Iluz-Cohen & Armon-Lotem, 2013; Morton & Harper, 2007; Prior & Gollan, 2011) it was expected that PED and proficiency would have positive effects on performance, such that individuals with higher PED and language proficiency would perform the task better. This was expected to be similar in both bilinguals and monolinguals. Interesting effects of language proficiency emerged in both groups. These effects call into question the "non-verbal" nature of this task as well as highlighting the differences between first and second language proficiency. Additionally, some support was given to the idea that bilingualism specifically tunes accuracy.

The goals of this study were both theoretical and methodological. Since much of the research done in the bilingual advantage realm includes tasks that have both reaction time and accuracy components, this study not only set out the examine the theoretical question of speed-accuracy tradeoffs in this group of interest but also to demonstrate the use of this powerful technique.

Experiment 1

Experiment 1 served to examine the relationship between reaction time and accuracy in a shape-color switching task in bilinguals and monolinguals.

Method

Participants and procedure. Previously collected data from 90 English monolinguals and 90 Spanish-English bilinguals were analyzed. All participants were recruited from the University of Houston Main Campus. The bilinguals all learned their second language, English, at or before age 9 (average age 5.4 years, SD 1.8). The English monolinguals reported no more than limited knowledge of any language other than English. Similarly, bilinguals reported little knowledge of any third language. Following consent procedures, participants were questioned about their knowledge and use of language, age of acquisition (AOA) of English (bilinguals only), demographic information, and parental education level (PED). Participants did not report neurological or psychiatric disorders, were not taking psychotropic medication, and had normal or corrected to normal vision. Following the demographic questionnaire and language assessments, participants completed three computer tasks, one of which was the shape-color task.

Shape-color rule switching task. In this task participants were shown blue or red circles or squares and were required to respond to either the shape or color of the stimulus depending on a cue. This task was administered using Eprime version 2.0 (http://www.pstnet.com/eprime.cfm). Each run began with instructions detailing the rule of response for the participants (e.g. “this run begins with color”). Participants responded with the index finger of both hands using the “m” and “z” keys of the keyboard. They were instructed to respond to a red shape or a circle using one hand and the a blue shape or a square using the other hand, depending on which rule they were following at the time, shape or color. Each response trial consisted of a red or blue circle or square presented at the center of the screen. Each stimulus remained on the screen for 500ms and was followed by a 1000ms blank screen. After 8-12 stimuli, participants were shown a cue. The cue was either a vertical dollar sign ($) or a horizontal dollar sign. A vertical dollar sign indicated to the participants that they should switch rules for the following trials. For example, if the participant had been responding to color, they should now be responding to the shape of the stimulus. A horizontal dollar sign indicated that participants should not switch and continue to respond using the rule they were just using (Figure 4).

Participants completed five runs of this task, each lasting 4 minutes and 5 seconds, and consisting of seven switch and seven non-switch events presented in random order. After completing all five runs, participants therefore had 35 instances in which they were required to switch and 35 non-switch events.

Data Analysis. Data from a total of 180 participants was used in this analysis. Trials for which there is no registered response were discarded. Any run with accuracy of less than 65% was discarded. As a result, 4 monolinguals and 4 bilinguals were removed from the sample resulting in 86 participants in each group. Switch trials were defined as the first trial following a switch cue for which a response was registered. Non-switch trials were defined as the first trial following a non-switch cue for which a response was registered. Both correct and incorrect trials were retained. Each participant was therefore presented with 35 switch and 35 non-switch events. In rare instances in which a participant did not respond to any stimuli between the presentation of one cue and the presentation of the next cue, those trials were removed from analysis. Additionally, if a participant was missing one or more of the five runs, due to a data collection error or because of a deletion for low accuracy, the remaining runs were used. Therefore some participants had fewer than 35 trials of each type, however for the majority of participants 35 trials of each type were analyzed. Reaction time data were log transformed and accuracy data were coded such that 1 = correct and 0 = incorrect.

Two identical multilevel structural equations models (ML-SEM) were estimated in Mplus (http://www.statmodel.com/), one for bilinguals (model 1, see Figure 2) and one for monolinguals (model 1', see Figure 3). Trials, the first level, was nested within person, the second level. Person-level latent variables for reaction time for each condition (switch and non-switch) were constructed from the individual trials. The same procedure was used to define accuracy variables. These reaction time and accuracy latent variables from each condition loaded on a general reaction time and a general accuracy latent variables, respectively. Upon examination of these models and given the non-significant trial-level correlation across groups and conditions it was decided to fit new models (models 2 and 2') without this correlation to improve model accuracy. Two identical models were fit, one for bilinguals and one for monolinguals.

Results

Model specification. Identical models for bilinguals and monolinguals were estimated in Mplus. Following the initial model evaluation (models 1 and 1'), it was decided to remove the trial-level correlation between reaction time and accuracy and estimate new models (2 and 2’). The results of the models are presented in Figures 5 and 6 for models 1 and 1’, and Figures 7 and 8 for models 2 and 2’, for bilinguals and monolinguals, respectively.

Hypotheses evaluation.

Hypothesis 1. Hypothesis 1 stated the expectation that trial level correlation between reaction time and accuracy will be positive, such that individual trials that are faster will be more likely to be incorrect. The correlation at the trial level could not be computed directly due to the categorical nature of the accuracy variable (correct/incorrect). A latent variable was used to estimate the relationship between reaction time and accuracy at the trial level. The variance of this variable as well as the factor loading of the accuracy value of the trial was fixed to 1. The factor loading of the reaction time of the individual trials was freely estimated. The meaning of this factor loading is the same as the trial-level correlation (parameters a, a’, b and b’ in Figures 2 and 3) between speed and accuracy. It was hypothesized that these correlations would be positive and significant in both groups and in both conditions. This hypothesis was not supported by the model outputs. The relationship at the trial level between reaction time and accuracy was not significant. In the bilinguals the trial-level correlations between reaction time and accuracy were -.003 and -.007 in the switching and non-switching conditions, respectively. In the monolinguals, these were -.008 and -.010 for switching and non-switching, respectively. All correlations had p-values greater than .05. This lack of significant correlation may be due to the fact that most trials for most people were correct, and there was not enough variability in accuracy across trials.

Hypothesis 2. Hypothesis 2 stated that the relationship between reaction time and accuracy at the person level would be significant and negative, such that people who have faster reaction times are also more accurate. This hypothesis was not supported. In examining the observed correlations in Tables 2 and 3, it does not appear that there is a relationship between reaction time and accuracy in either group. In the bilinguals the observed correlation between speed and accuracy in the switching condition was r=.1, p>.05, and in the non-switch condition r=-.14, p>.05. In the monolinguals the observed correlation was r=-.08, p>.05 in the switching condition and r=-.19, p>.05 in the non-switching condition. Because the observed correlations were so weak in both groups, it could be predicted that the latent variable correlation would also be weak and non-significant. The results of the model support this prediction. The correlations between reaction time and accuracy estimated by model 2, which were calculated across conditions, were .022 for bilinguals and -.181 for monolinguals, and both had p-values greater than .05. Similar to the lack of expected correlation between reaction time and accuracy at the trial level, it can be hypothesized that the lack of relationship at the person level may be due to relatively high accuracy levels in both groups across conditions.

Hypothesis 3. This hypothesis is perhaps the most similar to the traditional examination of the bilingual advantage. It regards the relationship between the switch and non-switch conditions in both groups. It was hypothesized that the two conditions would be more similar to one another in the bilingual group, which would indicate a result similar to smaller switch costs that have been found in previous studies using ANOVA. This hypothesis was evaluated by examining the factor loading ratios for the two conditions in bilinguals and monolinguals. Using models 2 and 2', the reaction time ratios were .904 for bilinguals and .899 for monolinguals. The accuracy ratios were 1.183 for bilinguals and 1.462 for monolinguals. Using confidence intervals, it can clearly be seen that there is no indication that the ratios of the two conditions in both reaction time and accuracy are different between groups (Table 4). The ratios are nearly identical, and the confidence intervals show a high degree of overlap across conditions. Following up the initial indications of a lack of difference, a model in which all four factor loadings were constrained to be equal across groups was compared to one in which the factor loadings for the two groups were allowed to vary. The constrained model did not fit the data significantly worse than the unconstrained model, $\chi^2(4) = 2.08, p > .05$, and it was determined that the factor loadings and the resulting ratios are not significantly different across groups. This hypothesis was therefore not supported by the results.

Hypothesis 4. This final hypothesis, suggesting that the trial level correlation between reaction time and accuracy will be greater in monolinguals compared to bilinguals, hinged on the retention of hypothesis 1, namely that this relationship would be significant in both groups. Since hypothesis 1 was not supported and there does not seem to be a significant trial-level relationship between reaction time and accuracy in either condition in either group, hypothesis 4 could not be logically evaluated.

Measurement Invariance. Measurement invariance was evaluated by comparing a model in which every parameter was constrained across group, i.e. all factor loadings and person-level correlation between reaction time and accuracy, to one in which these were allowed to vary. The results of a chi-square test indicate that the two models are not significantly different, $\chi^2(5) = 3.27, p > .05$, and therefore, that measurement invariance holds. This means that the task functions similarly in both groups, and that comparison of performance across groups is indeed valid.

Discussion

The main purpose of experiment 1 was to demonstrate the use of ML-SEM models for analysis of tasks with both reaction time and accuracy components. From a theoretical perspective, four hypotheses about the bilingual advantage were tested. Although none of the hypotheses were supported, the use of this technique for future studies is considered.

Contrary to hypothesis 1, there was no significant trial-level correlation between reaction time and accuracy in either group in any condition. It was originally hypothesized that individual trials that are faster will be more likely to be inaccurate. Similarly, hypothesis 2, which predicted a negative relationship between reaction time and accuracy at the person level, was also not supported. Given the high level of accuracy (bilinguals were 78% and 85% correct on average in the switching and non-switching conditions, respectively, and monolinguals were 78% and 86% correct in the switching and non-switching conditions, respectively) it is possible that there was not enough variability to discover these expected effects. In future studies, more difficult tasks can be utilized that would lead to greater variability in accuracy, and the trial-level and person-level relationships may be found.

With regard to hypothesis 3, which examined switching-costs, no bilingual advantage was discovered. Based on previous studies of the bilingual advantage in switching tasks it was expected that the bilinguals would perform more similarly on both conditions (switching and non-switching) than would the monolinguals. This was hypothesized to be the case in both reaction time and accuracy. The results of the study did not support this hypothesis, and it appears that monolinguals and bilinguals perform both task conditions similarly with regard to both speed and accuracy. Although these results do not support a proposed hypothesis, they were not unexpected; the theory of the bilingual advantage has been scrutinized and questioned in the past few years. Early studies of the bilingual advantage have been criticized for being misleading and utilizing inappropriate statistical analyses (Paap, Johnson, & Sawi, 2015). A publication bias towards publishing studies demonstrating a bilingual advantage compared to those that do not support it has also been alleged (de Bruin, Treccani, & Della Sala, 2014). Finally, and possibly most telling, recent large-scale replication efforts have failed to reproduce a bilingual advantage across different tasks and in a range of ages (Duñabeitia et al., 2014; Paap & Greenberg, 2013; Paap et al., 2014; Paap & Sawi, 2014).

Although it became apparent that this task did not produce a high enough level of variability in the accuracy of responses to make full use of this methodological approach, the introduction of this approach may serve to encourage the use of more difficult tasks. That is, without the possibility to examine the relationship between speed and accuracy it was necessary for studies to yield highly accurate results so that reaction time could be properly analyzed. In traditional examinations, reaction time from only correct trials is analyzed, and it was therefore necessary that whatever task was used had a high level of accuracy so that a larger proportion of trials could be used to analyze reaction time. The availability of this method that examines both reaction time and accuracy together removes this limitation on task design, and may encourage larger variability in task difficulty.

Experiment 2

In line with previous research, this experiment considered the effects both Parental Education (PED) and language proficiency may have on reaction time and accuracy.

Method

Participants and task. The same participant data that were was used in experiment 1 were used in experiment 2. In addition to performance on the shape-color rule switching task, participant reported PED and language proficiency were examined. Eight bilingual participants were missing information on one of the three covariates of interest, and were not included in the new model. As a result, 78 bilinguals and 86 monolinguals were included in experiment 2.

Language proficiency. The picture vocabulary and passage comprehension portions of the Woodcock-Muñoz Language Proficiency Battery—Revised (Woodcock & Muñoz-Johnson, 2005) were administered to participants. Bilinguals completed the test in both Spanish and English and monolinguals completed the English test only. The two subsets of the language proficiency assessment in each language were weighed equally and summed to create a single score for each individual (English only for monolinguals, English and Spanish for bilinguals).

Data analysis. Models based on models 2 and 2' were estimated with PED and language proficiency included as predictors at the individual person level of reaction time and accuracy latent variables for each condition. For bilinguals, Spanish proficiency, English proficiency, and PED were all entered in one model. For monolinguals, English proficiency and PED were entered. The proficiency variables were centered for each group at the group mean (e.g. English proficiency in the bilingual group was centered at the bilingual mean). PED was centered at a value equal to 3, indicating that the parent is a high-school graduate for both groups. Tables 2 and 3 list the means, standard deviations, and correlations for these variables along with observed accuracy and log transformed reaction time, calculated using

R. Because the models were evaluated with all covariates included, the relationship between the covariates and constructs of interest are computed as the independent contribution of each covariate, much like they would be computed in a standard multiple regression analysis.

Results

Model 2 was modified to include language proficiency and parental education level as predictors of reaction time and accuracy in each condition for both groups. Covariate estimates and p-values are listed in Table 5.

Bilinguals. In this group, it was found that English proficiency was a significant predictor of reaction time in both the switching, b=-.003, p=.02, and non-switching, b=-.003, p=.01, conditions. In both conditions, English was a negative predictor of reaction time, such that higher English proficiency predicted decreased reaction time. Spanish proficiency was a significant and positive predictor of reaction time in both the switching, b=.002, p=.03, and non-switching, b=.002, p=.04, conditions. In this case, higher Spanish proficiency predicted greater reaction time (slower performance). PED was not a significant predictor of any construct, and no covariates were significant in predicting accuracy in either condition.

Monolinguals. In this group, English proficiency significantly predicted accuracy in the non-switch condition, b=.046, p=.01, reaction time in the non-switch condition, b=-.003, p=.03, and reaction time in the switch condition, b=-.004, p=.01. Monolinguals with higher English proficiency performed both conditions faster (has smaller reaction time), and were more accurate in the non-switch condition. There were no significant predictors of accuracy in the switch condition. PED did not significantly predict accuracy or reaction time in either condition.

Discussion

Experiment 2 was focused on examining the effects individual differences in language proficiency and parental education level may exert on reaction time and accuracy in the shape-color task.

English proficiency was a significant predictor of reaction time in both conditions across groups. Individuals with higher English proficiency performed the task faster (had smaller reaction times). It is possible that all participants used a verbal strategy to contend with this task. There is reason to believe that even the bilinguals used English when completing the task. The majority of the session was conducted in English, with the exception of the Spanish language assessment. If it is the case that participants adopted a verbal strategy, it is logical that those participants with better English proficiency performed better. This hypothesis calls into question the validity of switching tasks, and I would argue other high-level cognitive tasks, as “non-verbal”. The relationship between high English proficiency and superior performance across groups suggests that there is a verbal component to this seemingly non-verbal task. It has been previously suggested that verbal switching and non-verbal switching are related, namely, the entire theory of the bilingual advantage rests on this assertion, but I argue that it may not possible to disentangle the two. In the future, following the administration of this and other high-level cognition task, it would be beneficial to poll the participants with regard to how they contended with the task.

The pattern of the opposite direction effect of Spanish proficiency on reaction time in the bilinguals is somewhat counterintuitive, however when considering the probable verbal nature of this task it becomes clearer. It appears that greater proficiency in the second language (English) decreases reaction time, while greater proficiency in the first language (Spanish) increases it. If indeed bilinguals are using English when completing the task, higher Spanish proficiency may interfere and cause confusion. As mentioned previously, there is reason to believe that the bilinguals were primed to use English for the duration of the session, and higher Spanish proficiency may hinder their ability to do so. It has been previously suggested that in order to utilize one language, bilinguals must constantly inhibit their other language. If bilinguals are highly proficient in a language it may be more difficult to inhibit it. In the context of performing this task, if bilinguals are using English during the task and have a higher Spanish proficiency, they may be exerting extra effort to inhibit Spanish leading to a detriment in performance. The opposite effect of Spanish and English proficiency on reaction time further support the notion that this task is not truly non-verbal. In most previous studies that considered language proficiency in adults, the focus has been on second language proficiency. It is therefore unknown whether the detrimental effect found in this study of first language proficiency on reaction time is a common finding. This somewhat counterintuitive relationship between the first language proficiency and reaction time on a switching task should therefore be examined further using different tasks to determine whether this is a universal phenomenon.

In the monolinguals, English proficiency was also a significant predictor of accuracy in the non-switch condition. This difference between monolinguals and bilinguals suggests that bilingualism may tune accuracy. In their daily lives, bilinguals must be accurate; they must select the appropriate language depending on the context (i.e. the person they are conversing with), and generally contend with this task very well. Bilinguals can therefore be thought to “train” the accuracy component of switching and inhibition, while reaction time is not similarly trained. In the monolinguals, where no such accuracy training is present, greater English proficiency is associated with better accuracy, similar to the relationship between proficiency and reaction time. In the bilinguals, there is no relationship between English proficiency and accuracy. This lack of relationship may be due to bilinguals' constant emphasis on accuracy, which serves to minimize any effect individual differences in proficiency may have. Because bilingualism does not necessarily tune reaction time, the effects of English proficiency on speed are very similar in bilinguals and monolinguals.

This present study joins the ranks of those that have failed to find a bilingual advantage, however it also suggests that the story is not necessarily as simple as "do bilinguals outperform monolinguals on tasks of executive function," but rather "does training in the form of bilingualism alter general executive function mechanisms?" The second question does not assert an advantage for bilinguals over monolinguals but rather serves to make a connection between language experience and executive control. This alternative view has also been referred to in a recent publication from our lab (Vaughn, Greene, Ramos, & Hernandez, 2015).

General Discussion

The primary goal of this examination was to investigate the bilingual advantage in a novel way, focusing on the relationship between reaction time and accuracy and effects of individual differences as opposed to on the differences between conditions. The secondary—and no less meaningful—goal of this investigation was to develop a new methodological approach that can be used to analyze data that includes both reaction time and accuracy components. The benefits of this approach are numerous: both traditional and novel hypotheses (e.g. ratio differences and differences in correlations across levels) can be examined using the same analysis, there is no longer a need to separate two variables that have been known for decades to be related to one another, the addition of covariates is possible and interpretation clear, and the model is intuitive, graphical, and easily interpretable.

Although from a substantive and methodological perspective the most innovative hypotheses were not supported and the power of this new method could not be showcased, the results of this study revealed a number of interesting findings that are worthwhile to investigate in future studies. First, it was discovered that this switching task operates in a very similar manner in both bilinguals and monolinguals. This finding validates the use of this task to compare bilinguals and monolinguals, and may encourage future experimenters to either use this task or similar variants, or run similar analyses and test their own tasks for measurement invariance when comparing groups. Second, this study questions the notion that shape-color switching tasks are non-verbal, because language proficiency is clearly related to task performance. In the future, when utilizing so-called non-verbal tasks, it would behoove researchers to account for the verbal nature of tasks and either interview their subjects regarding the strategy they used or include an articulatory suppression aspect to the task to ensure minimal verbal intrusion on task performance. Finally, and in support of the verbal nature of this task, it was discovered that higher first language proficiency is detrimental to task performance. Many previous studies did not examine the role of language proficiency at all, and those that did consider language proficiency often did not examine the role of first language proficiency. Given this inverse relationship between first and second language proficiency and the heavy theoretical implications, it is my hope that in the future the role of both first and second language proficiency will be examined.

In sum, this project resulted in a number of interesting findings, although none of the original hypotheses were supported. I hope that the availability of this method would encourage a shift in task design that would allow us as a field to test exciting new hypotheses, as well as serve to caution over-reliance on the “non-verbal” nature of cognitive tasks and encourage consideration of verbal abilities of participants.

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Table 1

Results from Prior and MacWhinney (2010)

			Mixed-task blocks	
		Single-task blocks	Non-switch	Switch
Bilingual	RT	437.97 (11.2)	670.16 (28.7)	814.16 (33.2)
	% correct	95.9	94.2	91.8
Monolingual	RT	448.8 (11.8)	669.05 (26.7)	875.54 (39.2)
	% correct	97.8	96.1	92.2

Reaction time (in milliseconds) and percent accuracy for bilinguals and monolinguals in the shape-color task.

Table 2

Means, standard deviations, and correlations of observed variables in bilinguals

	Mean	SD	Eng.prof	Spa.prof	PED	meanlogswrt	meanaccsw	meanlognswrt	meanaccnsw
Eng.prof	74	5.26	1	0.42**	0.3*	-0.2	0.19	-0.2	0.03
Spa.prof	77	6.45		1	0.35*	0.08	-0.04	0.06	-0.19
PED	2.96	1.41			1	-0.13	0.02	-0.17	-0.16
meanlogswrt	2.7	0.07				1	0.1	0.75**	0.1
meanaccsw	0.78	0.12					1	-0.14	0.77**
meanlognswrt	2.67	0.06						1	-0.14
meanaccnsw	0.85	0.11							1

n=78
**= $p < .001$
*= $p < .01$

Table 3

Means, standard deviations, and correlations of observed variables in monolinguals

	Mean	SD	Eng.prof	PED	meanlogswrt	meanaccsw	meanlognswrt	meanaccnsw
Eng.prof	80	5.74	1	0.11	-0.31**	0.19	-0.26*	0.25*
PED	4.38	1.05		1	-0.17	-0.03	-0.12	0.02
meanlogswrt	2.66	0.08			1	-0.08	0.84***	-0.16
meanaccsw	0.78	0.13				1	-0.03	0.6***
meanlognswrt	2.63	0.07					1	-0.19
meanaccnsw	0.86	0.12						1

n=86
***= $p < .001$
**= $p < .01$
*= $p < .05$

Table 4

95% Confidence Intervals for reaction time (RT) and accuracy factor loading ratios

	Estimate	Lower 2.5%	Upper 2.5%
Bilinguals			
RT	0.904	0.753	1.055
Accuracy	1.183	0.92	1.447
Monolinguals			
RT	0.899	0.789	1.008
Accuracy	1.462	1.051	1.873

Table 5

Results from regression of latent variables on PED and proficiency

	Switch RT	Non-switch RT	Switch accuracy	Non-switch accuracy
Bilinguals				
PED	-0.008	-0.007	0.02	-0.053
Spanish proficiency	.002*	.002*	-0.019	-0.031
English proficiency	-.003*	-.003*	0.036	0.023
Monolinguals				
PED	-0.01	-0.006	-0.036	0.025
English proficiency	-.004**	-.003*	0.023	.046*

**= $p < .01$
*= $p < .05$

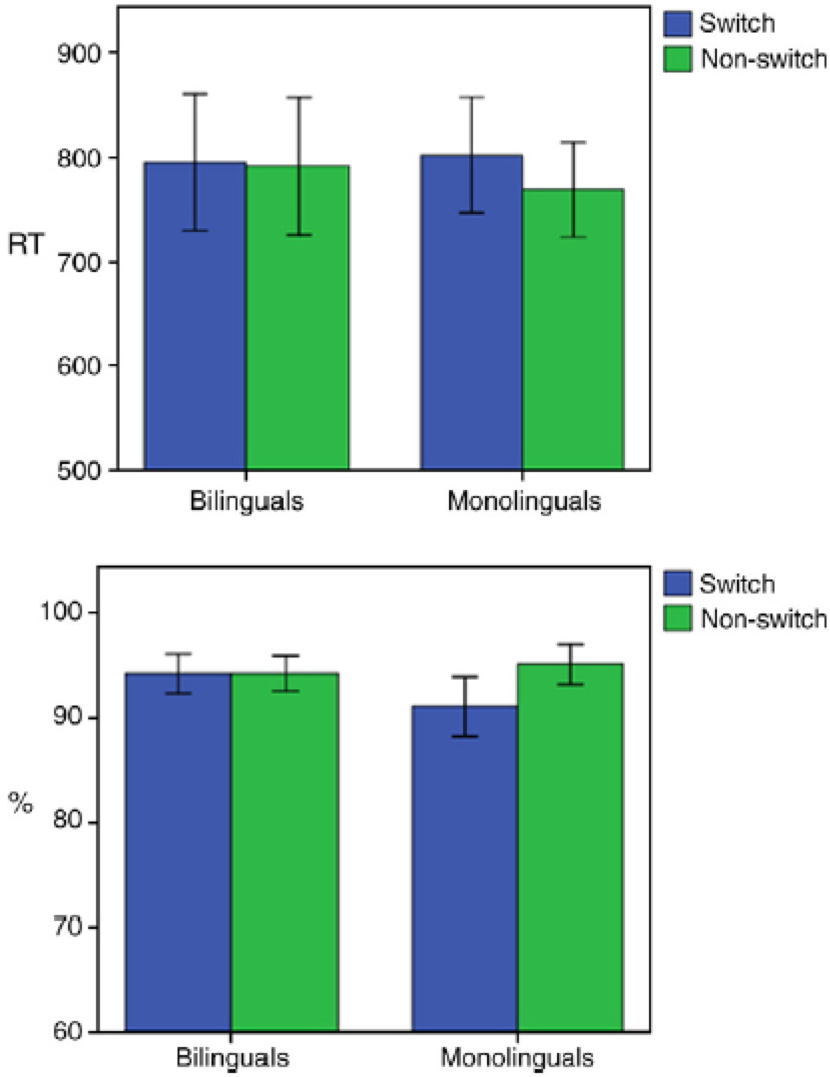

Figure 1. *Results from Garbin et al. (2010). Average reaction time (in milliseconds) and percent accuracy for bilinguals and monolinguals for switch and non-switch condition. Monolinguals presented with larger switching costs in accuracy and reaction time (marginally significant).*

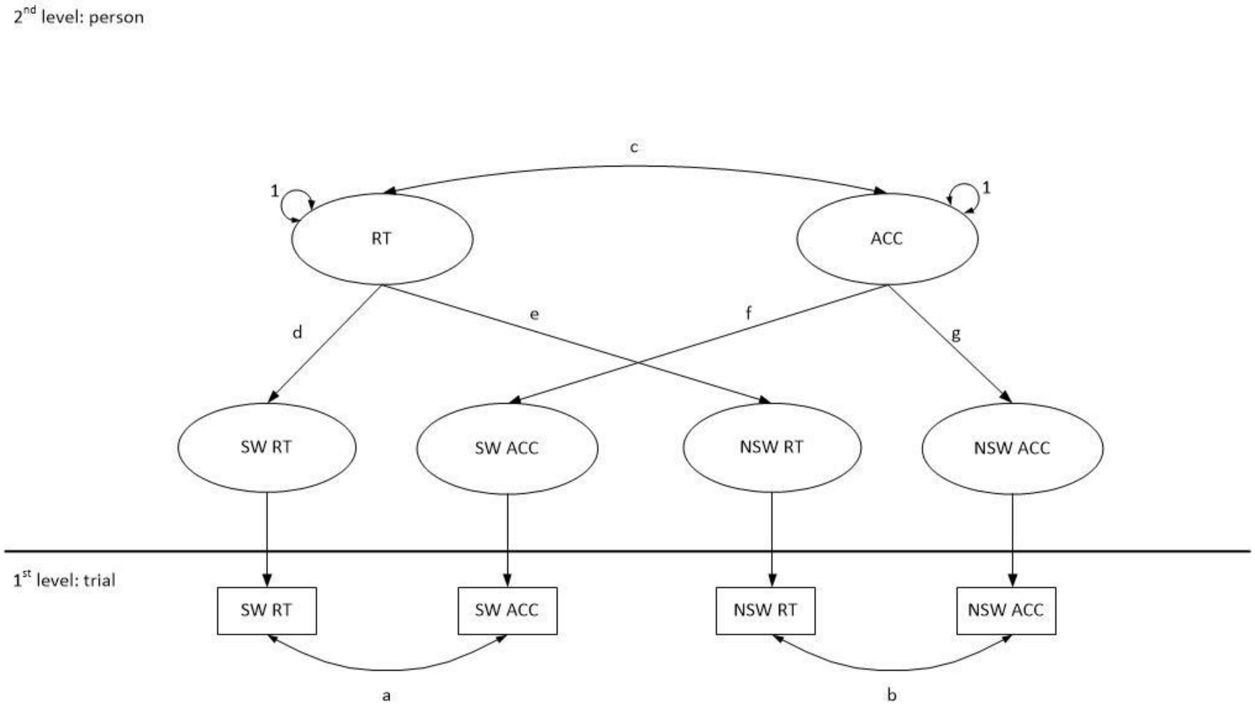

Figure 2. *Model 1 for reaction time (RT) and accuracy (ACC) in bilinguals, where SW=switch condition, and NSW=non-switch condition*.

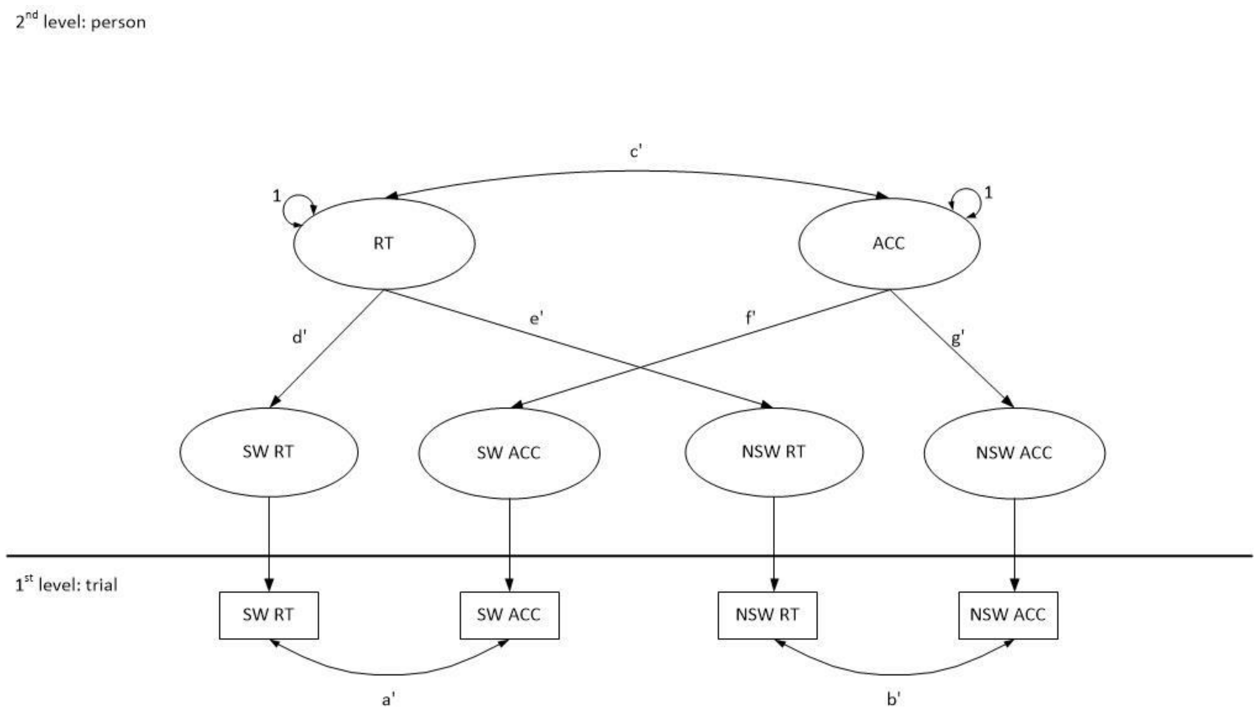

Figure 3. *Model 1' for reaction time (RT) and accuracy (ACC) in monolinguals, where SW=switch condition, and NSW=non-switch condition*.

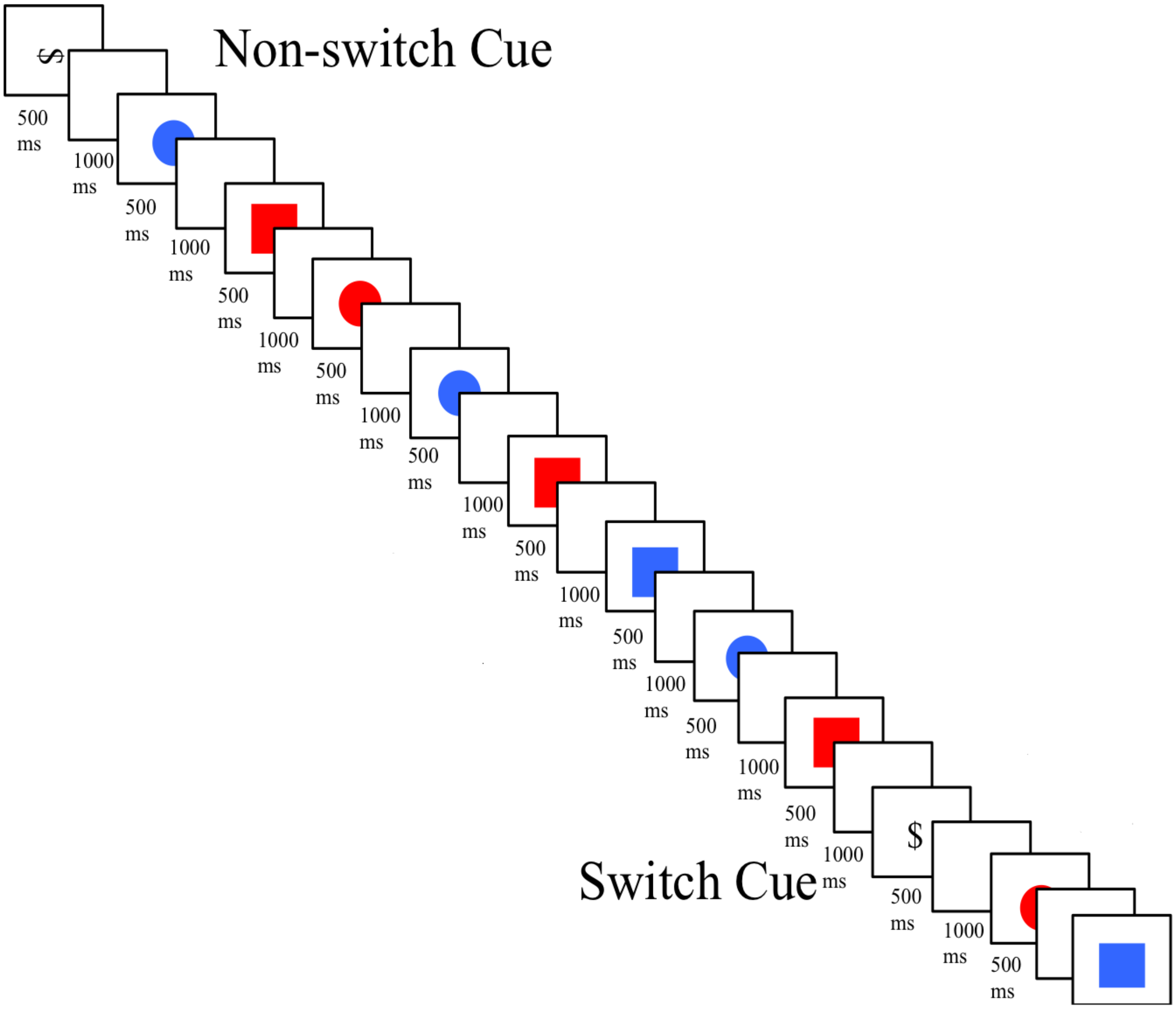

Figure 4. *Sample shape-color task trials. Participants must respond to individual trials according to a specific rule (shape or color). If a non-switch cue is presented, participants continue to respond using the same rule (e.g. shape→shape). If a switch cue is presented, participants switch and respond using the other rule (e.g. shape→color).*

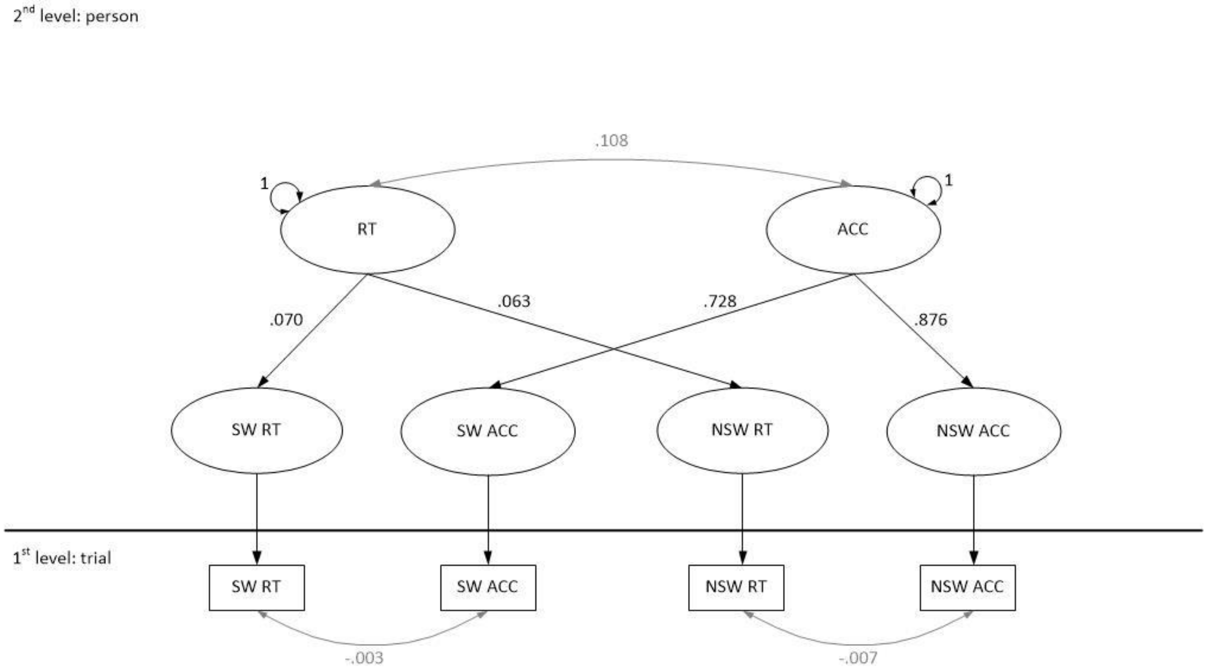

Figure 5. *Model 1 results for bilinguals. All factor loadings significant at* $p \leq .001$. *Gray=not significant*.

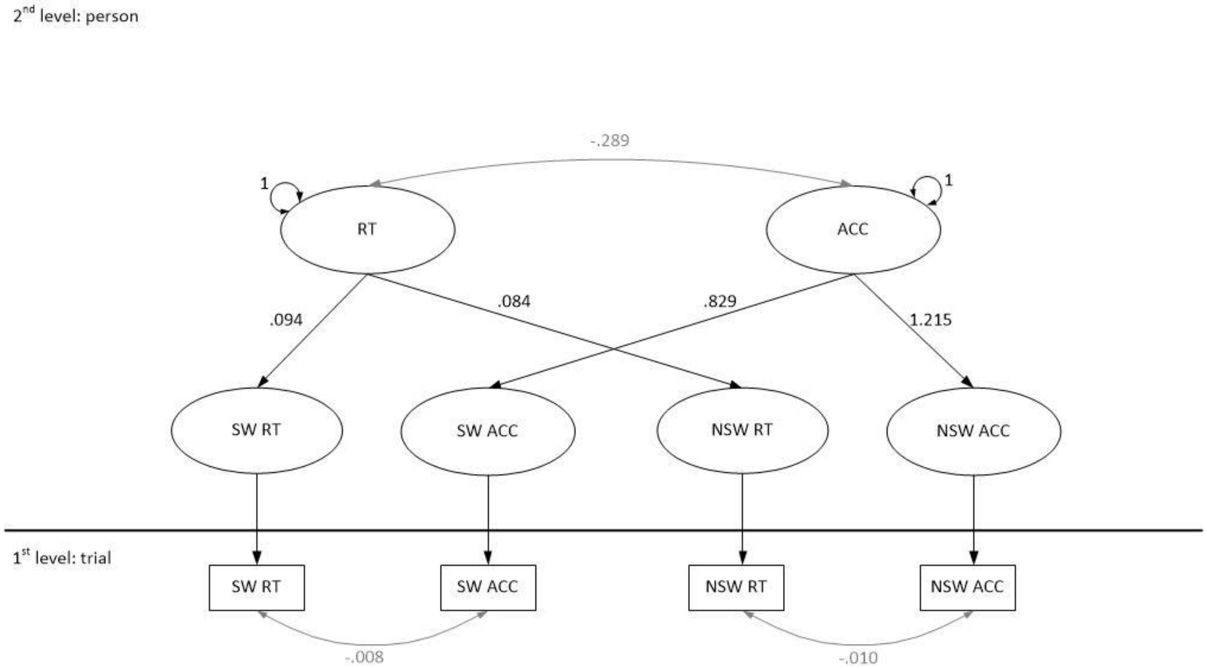

Figure 6. *Model 1' results for monolinguals. All factor loadings significant at* $p \leq .001$.

Gray=not significant.

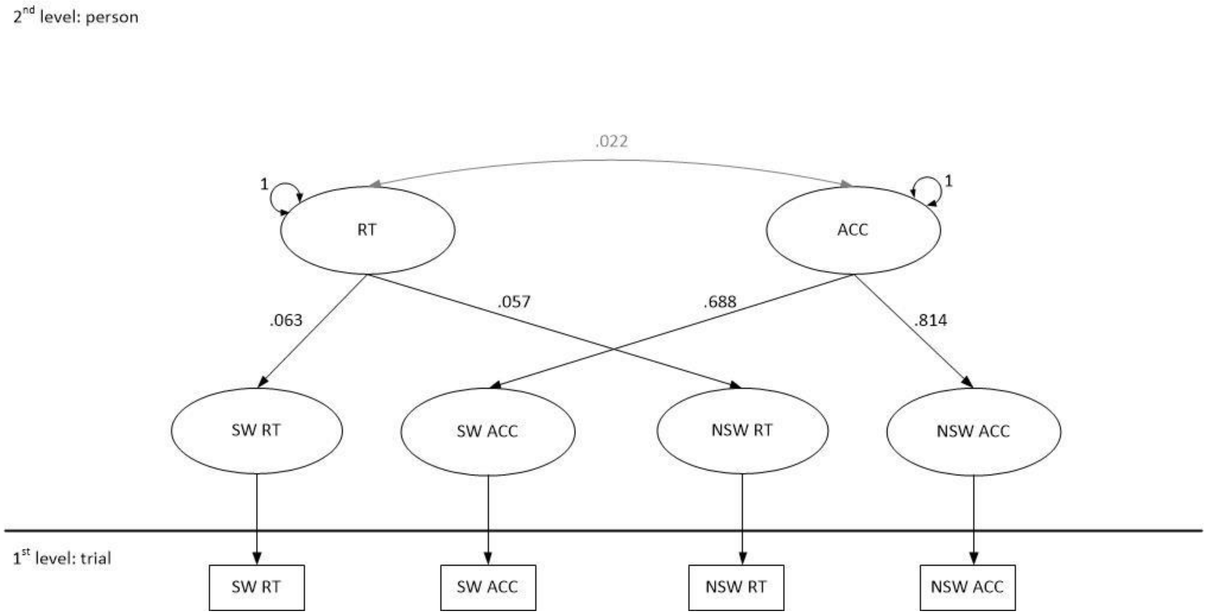

Figure 7. *Model 2 results for bilinguals. All factor loadings significant at* $p \leq .001$.

Gray=not significant.

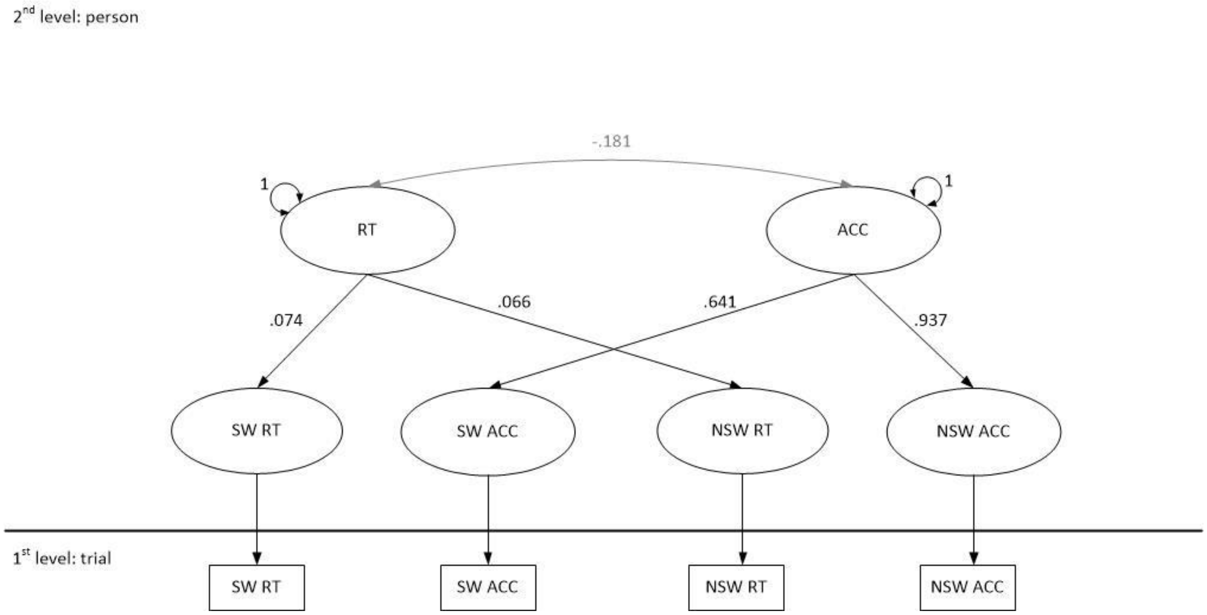

Figure 8. *Model 2' results for monolinguals. All factor loadings significant at* $p \leq .001$.

Gray=not significant.