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Behavioural and ERP correlates of bilingual language control and general-purpose inhibitory control predicted by L1 and L2 proficiency

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ABSTRACT

Cognitive control is the ability to adapt flexibly to current demands by promoting task-relevant information in the face of interference, and this has been asserted as an advantage with bilinguals. Bilingual language control and general-purpose cognitive control are discussed in the literature using different types of stimuli, cognitive tasks, component processes (selection, interference, inhibition, switching) and groups (bilingual vs. monolingual; high proficient vs. low proficient bilingual). The present study was designed to investigate the neurocognitive correlates of inhibitory control with linguistic (i.e., words) and nonlinguistic (i.e., line drawings of objects) stimuli in Hindi-English bilingual adults. We conducted the behavioural experiment first to establish the linguistic version of identity negative priming paradigm followed by the Event-related potential (ERP) experiment using the linguistic and nonlinguistic negative priming task. Results show the presence of inhibition effect using mean reaction times as well as ERP data while comparing the control and ignored repetition conditions, and this pattern varied with different stimuli – linguistic vs. nonlinguistic. Thus, the current study suggests that bilingual language control is not entirely subsidiary to general-purpose cognitive control and shows differences based on the stimulus type. Also, proficiency in L1 and L2 differentially predicts performance on the nonlinguistic and linguistic negative priming paradigm, respectively. These results are indicative of a dynamic cognitive control system associated with bilingualism, which varies as a function of stimulus type as well as language proficiency.

1. Introduction

Over the years, it has been established that speaking two or more languages appears to have a positive effect on cognitive control in bilinguals. Bilingual cognitive advantage is usually defined as the individual differences in cognitive task performances resulting in a better response time and fewer errors in different paradigms like Go/No-Go, Flanker task, Simon task, and Attention network task (Rodrigues-Fornells, Balaguer & Munte, 2007; Costa, Hernandez & Sabastian-Galles, 2008; Bialystok, Craik, Klein & Viswanatha, 2004). This advantage develops over time with the juggling of the two languages resulting in Bilingual language control (bLC) ability, which is transferred to the General-purpose cognitive control ability (GPCC[1]; Green, 1998; Abutalebi & Green, 2007; Calabria, Costa, Green, & Abutalebi, 2018). Bilingual language control involves similar cognitive processes that are proposed for the general-purpose

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[1] General-purpose cognitive control (GPCC) can be synonymously used with executive function, cognitive control, or domain-general cognitive control and it involves the ability to effectively perform multiple tasks as efficiently as possible.

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cognitive control system and consist of an overlapping neural correlate (Calabria, Baus, & Costa, 2019). However, the association between general-purpose cognitive control and bilingual language control (bLC) is debatable. Some studies suggest an overlap between the bLC and GPCC (Dash & Kar., 2014; Declerck, Grainger, Koch, & Philipp, 2017; Green & Abutalebi, 2017; Prior & Gollan, 2011), and other studies consider both being distinct processes – lack of overlap between bLC and GPCC (Branzi, Calabria, Boscarino, & Costa, 2016; Calabria, Hernández, Branzi, & Costa, 2012; Jylkkä, Lehtonen, Lindholm, Kuusakoski, & Laine, 2018; Segal, Stasenko, & Gollan, 2019). For instance, Prior and Gollan (2011) showed similar language and task switch costs in Spanish English bilinguals, suggesting that language switching affects domain-general cognitive control. On the contrary, Declerck, Eben, and Grainger (2019) found no overlap between language control and executive control using a bilingual and a nonlinguistic flanker task. Interestingly, these studies compared linguistic and nonlinguistic versions of the cognitive control tasks, measuring different subcomponents of cognitive control (i.e., switching or goal shifting, inhibition, monitoring etc), but none of these studies compared the performance within the bilingual population based on the level of language proficiency as a measure of bilingualism. The current study examined the influence of language proficiency (i.e., L1-Hindi and L2-English) on bLC and GPCC – using linguistic and nonlinguistic stimuli – in an identity negative priming paradigm that measures inhibitory control.

The interaction between bilingualism and cognitive control is studied extensively in different language groups using electrophysiological measurement (Abutalebi, Annoni, Zimine, Pegna, Seghier, Jahnke et al., 2008; Crinion, Turner, Grogan, Hanakawa, Noppeney, Devlin et al., 2006; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Rodriguez-Fornells, Schmitt, Kutas, & Munte, 2002). Rodriguez-Fornells, Balaguer, and Münte (2006) have demonstrated the involvement of control mechanisms through frontal-central negativity observed at about 400 ms (ms) for cross-linguistic interference at the phonological and syntactic level. Jackson et al. (2001) conducted ERP studies with 20 native English speakers and with different languages as L2. Larger left frontocentral negativity was observed in the switch trials as compared to non-switch trials. Bilingualism does not have an equal impact on all the subcomponents of cognitive control – selection, inhibition, and switching (Hernández, Costa, & Humphreys, 2012; Bialystok, Craik, & Luk, 2012). Therefore, the selection of appropriate experimental task is crucial. Negative priming paradigm – measuring inhibitory control – is an ideal task to examine the effect of the previous trial on the current trial, thus introducing a high monitoring demand on each trial.

Negative priming occurs when responses to a target stimulus is slower in a situation when the same target stimulus is present as a distractor in the previous trial. Although, negative priming is a well-established paradigm to measure the effect of inhibitory control that is viewed as a consequence of the competing irrelevant stimuli from the previous trial that needs to be inhibited for current trial target selection (D'Angelo, Thomson, Tipper & Milliken, 2016), there are limited studies measuring the effect of bilingualism using a location-based negative priming paradigm (Blumenfeld & Marian, 2011; Treccani, Argyri, Sorace & Della Sala., 2009). The findings from these studies suggest that bilinguals have a more efficient inhibition mechanism when compared to monolinguals. Moreover, there are fewer studies that supports the inhibitory account of the cross-language negative priming effects using word stimuli monolingual context; Macizo, Bajo, & Martín, 2010; Martín, Macizo, & Bajo, 2010; (bilingual context; Neumann, McCloskey, & Felio, 1999; Neumann, Nkrumah, & Chen, 2018; Nkrumah & Neumann, 2018). The goal of these studies, however, was not to look at the bilingual advantage in inhibitory control mechanism but rather look at the bilingual language processing and representation. Interestingly, none of these studies look at the effect of bilingual language proficiency on the inhibitory control mechanism. Moreover, the bilingual cognitive control studies are often challenged and criticized due to various methodological issues – selection criteria of participants, stimulus types, task demands, experimental designs or subcomponent processes under study (Costa, Hernander, & Sabastia-Galle, 2008; Grosjean, 1998; Hilchey & Klein, 2011; Paap & Greenberg, 2013; Saidi & Ansaldo, 2015). With the overwhelming criticism on bilingual benefits (Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Hilchey & Klein, 2011; Paap & Greenberg, 2013; Saidi & Ansaldo, 2015), there is a need for methodological precision, more so, while defining and measuring bilingualism. Bialystok (2001) and Grosjean (1998) advocate for the notion of language proficiency as a continuous variable to address individual variability in performance, which was found to be particularly true in the Indian context with a complex linguistic environment (Dash & Kar, 2012). There is a gradual shift from the traditional ways of categorizing the bilingual population (Bialystok et al., 2012; Bialystok & Feng, 2009; Costa, Hernender & Sabastia-Galle, 2008; Siegal, Lozzi, & Lurian, 2009) to considering measures of bilingualism as a continuous variable (Anthony & Blumenfeld, 2018; Dash, Berroir, Joanette, & Ansaldo, 2019; Dash & Kar., 2012; Goral, Campanelli, & Spiro, 2015; Incera & McLennan, 2018; Yow & Li, 2015). Dash and Kar (2012) highlighted another important implication of a complex linguistic environment. Different patterns of clustering were observed in both the languages on proficiency tasks (i.e., L1-Hindi and L2-English), i.e., L2 tasks are clustered at the domain level (speaking/understanding tasks forming one cluster, for example) whereas L1 tasks showed skill-specific clusters (i.e., metalinguistic skills grouped as one component) (Dash & Kar, 2012). Studies on bilingual cognitive control are primarily based on comparisons of bilinguals and monolinguals, which may or may not generalize while considering language proficiency as a continuous variable.

Research on bilingualism often considers only L2 proficiency to interpret the effects of bilingualism on control processes. Given the variability in the organization of both the languages, both L1 and L2 skills need to be considered while interpreting experimental data. The current study is an investigation of the behavioural and electrophysiological correlates of inhibitory control among bilinguals varying in the level of L1 and L2 language proficiency. The negative priming paradigm with linguistic and nonlinguistic stimuli was employed to look at the inhibition mechanisms operating in the current trial as a function of previous trial effects. We used comparable identity negative priming tasks for both linguistic and nonlinguistic stimuli in two separate experiments to examine the influence of language proficiency on bLC and GPCC. We also intended to examine the relationship between L1 and L2 proficiency – treated as a continuous variable. The current study consists of two parts. In Experiment 1, the linguistic version of identity negative priming was validated in the behavioural paradigm. Study 2 consists of the ERP version of identity negative priming with both linguistic and nonlinguistic stimuli. The change in the amplitudes of the N200 component was examined as a measure of inhibition and conflict monitoring. We expected an inhibitory control effect for both linguistic and nonlinguistic tasks suggesting commonality between the bLC and GPCC. We also expected to find a significant relationship between L1 and L2 proficiency and inhibition effect with nonlinguistic stimuli in Experiment 2, given the findings supporting the relationship between general cognitive control mechanisms and language control.

Experiment 1: Cross-linguistic negative priming

A cross-linguistic negative priming task was designed with overlapping words in Hindi and English, where one of the two overlapping words was attended (and the other was ignored) on a given trial. Current trial reaction times were expected to vary as a function of the previously activated/suppressed language. It was hypothesized that the inhibition effect would be higher for L1 as compared to L2.

.1. Method

.1.1. Participants

Twenty, right-handed Hindi-English bilingual adults (Mean age: 21.75 years, ± 3.2 SD, with 7 males and 13 females) participated in the experiment. All participants were native speakers of Hindi (L1) and learned English (L2) in a more formal setting with at least 7 years of education in both languages, used both the languages in daily use, and with no significant history of sensory/motor/neurological disorders, were taken for the study. Participants were selected randomly from the University of Allahabad and provided written informed consent. The study was approved by the Institutional Ethics Committee, University of Allahabad.

.1.2. Measures of bilingualism

Language history questionnaire (Vasanta, Suvarna, Sireesha, & Bapi Raju, 2010) was administered to collect information related to language acquisition, context of language acquisition, present language use (in percentage), language preference, use of language with family, friends, extended family, neighbours and respective hours of usage (per day), medium of instruction and self-reported proficiency level on different domains (5 point rating, where 1 represented "*poor*" and 5 represented "*excellent*"). All this information was organized under three major headings: age-related self-reported information; use related self-reported information and proficiency related self-reported information. The administration of the questionnaire took approximately 20–30 min for each participant (Appendix 1a).

Test of language proficiency in Hindi and English: An indigenously developed test of language proficiency in Hindi and English consisting of different tasks under the domains of speaking/understanding and reading/writing was employed (Dash & Kar, 2012). Speaking/understanding domain consisted of both production and comprehension tasks, which measured the level of performance at lexical, syntactic as well as discourse levels. These tasks included confrontation naming task, discourse analysis, convergent production/synonym tasks, and auditory comprehension. Similarly, the reading/writing domain consisted of tests for reading comprehension, fluency, phonological awareness, and written discourse. Performance on each test was measured in terms of accuracy percentage and was added to the composite score for each domain, namely speaking/understanding and reading/writing. The questionnaire and the proficiency test were individually administered in a quiet, well-lit room (Appendix 1b).

.1.3. Negative priming task

Stimuli and Procedure: The stimuli for identity negative priming consisted of a display containing overlapping linguistic stimuli (words in Hindi and English) in two shades of gray at the center of the screen. The words were taken from a set of 303 words (both language translation of the pictures from Abbate & LaChapelle, 1984) in both languages out of which a total of 120 words were selected (60 in each language), they were matched in length in both the languages and consisted of both animate and inanimate words (60 animate as well as inanimate), which resulted in 240 stimuli after overlapping these words. Each word was repeated twice in different combinations, thus resulting in 60 combinations for language and animacy (Hindi Animate = 60, Hindi Inanimate = 60, English Animate = 60, English Inanimate = 60). Words were selected based on the ratings on frequency, imageability, and familiarity levels of each word on a 5 point rating scale (where 1 represented "least" and 5 represented "most". 20 high proficient Hindi-English Bilinguals (Mean = 21.34 years, SD = ± 2.3) participated in the rating process and words with average rating were selected (Frequency: Mean = 3.67, SD = 0.75; Imageability: Mean = 4.24, SD = 0.61; Familiarity: Mean = 4.56, SD = 0.64).

The pairs of trials were structured according to a prime-probe schema. The stimuli consisting of overlapping meaningful words were presented in such a manner that the current stimulus acted as a prime for the upcoming stimulus and probe for the previous stimulus. There were four kinds of prime-probe combination trials with both prime and probe stimuli being monolingual, monolingual prime stimulus – bilingual probe stimulus, bilingual prime stimulus –monolingual probe stimulus, and both prime and probe with bilingual stimuli (see Fig. 1 and Table 1). RGB coordinates (157,157,157) defined the target. The assignment of color cue for the target word was counterbalanced across participants, i.e., half of the participants responded to the stimulus in the shade of light gray and other half responded to words in the shade of dark gray. 2 different pseudo-randomized lists were created for both dark and light versions of the experiment. None of the pairs of words presented in a particular trial or successive trials were semantically or phonologically related.

The stimuli were presented on a 17″ monitor in a quiet, dimly lit room. The stimuli appeared at the center of the screen, measuring within the frame of 106 pixels * 52 pixels. A horizontal and vertical resolution was fixed to 71dpi. Each trial began with a fixation point for 400 ms at the center of the screen followed by the pair of words against a white background for 200 ms, after which

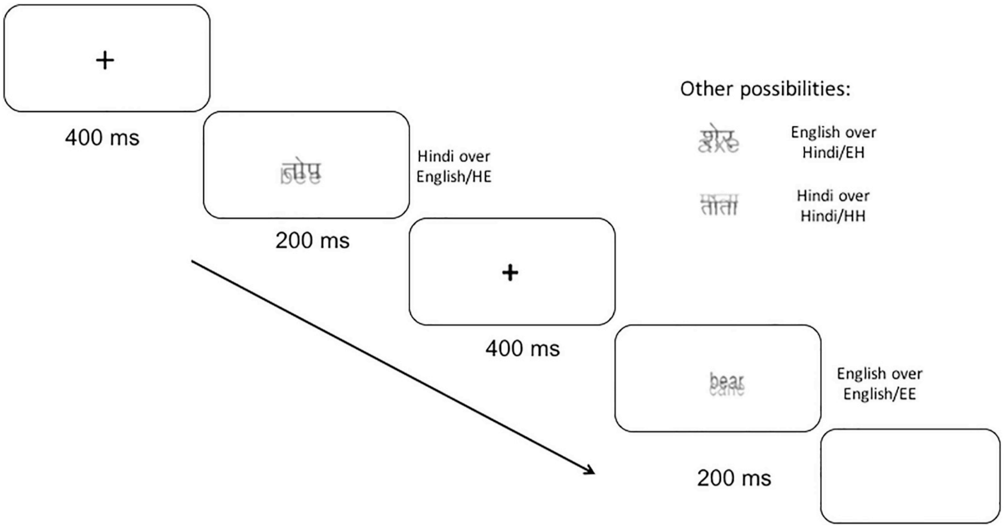

Fig. 1. Temporal sequence of the stimuli presentation along with the examples of the different stimuli type used in the study 1.

a blank screen was presented, and it stayed until response followed by a fixation point for the next trial. Participants performed an animacy judgement task once the stimuli appeared on the screen and responded by pressing the left arrow key if the target word represented an animate object and right arrow key if the target word represented an inanimate object. Participants responded using the first and second fingers of their dominant hand. Participants were instructed to respond as quickly and as accurately as possible. Overlapping words were presented in different combinations, i.e., Hindi over Hindi, English over English, Hindi over English, and English over Hindi (see Table 1). The stimuli were presented in the ratio of 3:1 for attended repetition and ignored repetition conditions. Attended repetition condition (336 trials, 168 monolingual, and bilingual trials each) consisted of trials in which the target language in the current trial was the same as the one in the previous trial. Ignored repetition condition (144 trials, 72 monolingual and bilingual trials each) consisted of trials in which the target language in the current trial was a distractor and hence was ignored on the previous trial. Other than the two priming conditions, there were four possible prime-probe combinations, as mentioned above, due to the two languages in which stimuli were presented. Also, the pure switch trials with a monolingual prime stimulus followed by a monolingual probe stimulus with one in L1 and another in L2 or vice versa were retained to partial out the effect of pure switch between the two languages and to bring out the true effect of persistent inhibition.

.1.4. *Data analysis*

Reaction time (RT) data were analysed for the two priming conditions (attended repetition and ignored repetition), each having four types of prime-probe combination trials (monolingual-monolingual, monolingual-bilingual, bilingual-monolingual and bilingual-bilingual) for both the languages. Error trials (9.2%) and those with RTs that were more than 3SD (1.5%) were excluded from further analysis. Cross-linguistic inhibition effect is said to occur when responses to target language are slower in a situation when the target language was presented as a distractor on the previous trial. To examine the cross-linguistic inhibition effect, we computed difference scores using RTs across the prime-probe combination. Since the stimuli included words from both the languages, switching effects were bound to occur in addition to the cross-linguistic inhibition effect. To rule out the effect of language switching effect due to the pure-switch trials, simple subtractions were performed. Difference scores for the bilingual prime trial followed by monolingual probe trial in the attended repetition condition (for example, EH followed by EE where English is the target language in both the combinations) were further subtracted from the pure switch condition (HH followed by EE), same for the ignored repetition condition. Similarly, difference scores for the bilingual prime trial followed by bilingual probe trial in the attended repetition condition (for example, EH followed by EH where English is the target language in both the combinations) were further subtracted from the no switch condition (EE followed by EE); same for ignored repetition (see Table 1 for details). This resulted in 2 versions of priming conditions for both attended repetition and ignored repetition – monolingual-bilingual prime-probe combination (i.e., H1 and E1) and bilingual prime probe combination (i.e., H2 and E2) Means of the difference scores of both prime-probe combinations (with standard error of mean) as a function of language and priming Bilingual-monolingual prime-probe combination was not considered for analysis based on the non-significant effect of this combination of trials on the inhibition effect as observed in the pilot study.

Bivariate correlation and regression analysis were performed to examine the relationship between measures of bilingualism and negative priming task performance. Multiple regression analysis was performed by using the simultaneous method. Results of correlation and regression analysis are discussed for the speaking/understanding and reading/writing domains of language skills (measured using the test of language proficiency).

.2. Results

The difference scores were then subjected to a three-way, 2 languages (Hindi/English) * 2 priming conditions (Attended repetition/ignored repetition) * 2 prime-probe combinations (H1/E1 and H2/E2) repeated measures ANOVA (see Fig. 2). There was a significant main effect of priming condition, indicating that ignored repetition trials were slower than attended repetition trials [$F(1,19) = 6.38$, $p = 0.021$]. The main effect of prime-probe combination and the interaction between language and prime-probe combination was not significant, [$F(1,19) = 2.54$, $p = 0.12$ and $F(1,19) = 1.17$, $p = 0.29$ respectively]. However, the interaction effect between priming condition and prime-probe combination was significant, $F(1,19) = 8.77$, $p = 0.008$. Post hoc comparisons showed a significant effect for the bilingual prime-probe condition only. The interaction between language and priming condition showed a trend of significance, [$F(1,19) = 4.37$, $p = 0.05$. The three-way interaction of language, priming condition and prime-probe combination was significant [$F(1,19) = 12.81$, $p = 0.008$]. Tukey's post hoc test for the three-way interaction further confirmed significant inhibition effect for the set of bilingual prime-probe combination (H2/E2) in both the languages ($p = 0.043$ for L1 and $p = 0.0002$ for L2), which indicates that when the weight of the prime and probe trial was the same (when both prime and probe trials had bilingual stimuli), inhibition effect was seen in both the languages and magnitude of this effect was more for L1 as compared to L2. This is to say that the sustained effect of inhibition was found to be greater for L1 as compared to L2.

Table 1
Prime and probe combinations employed in experiment 1, along with the method to calculate the difference scores.

Attended repetition	Ignored repetition	Switch/no switch
English attended	English ignored	Hindi switch
EH followed by EE (1)	EH followed by EE (5)	HH followed by EE (9)
EH followed by EH (2)	EH followed by EH (6)	English switch
Hindi attended	Hindi ignored	EE followed by HH (10)
HE followed by HH (3)	HE followed by HH (7)	Hindi no switch
HE followed by HE (4)	HE followed by HE (8)	HH followed by HH (11)
		English no switch
		EE followed by EE (12)
Calculation of difference scores:		
Monolingual-bilingual prime-probe combination:		
	Attended repetition	Ignored repetition
H1	3 minus 10	7 minus 10
E1	1 minus 9	5 minus 9
Bilingual-bilingual prime-probe combination:		
	Attended repetition	Ignored repetition
H2	4 minus 11	8 minus 11
E2	2 minus 12	6 minus 12

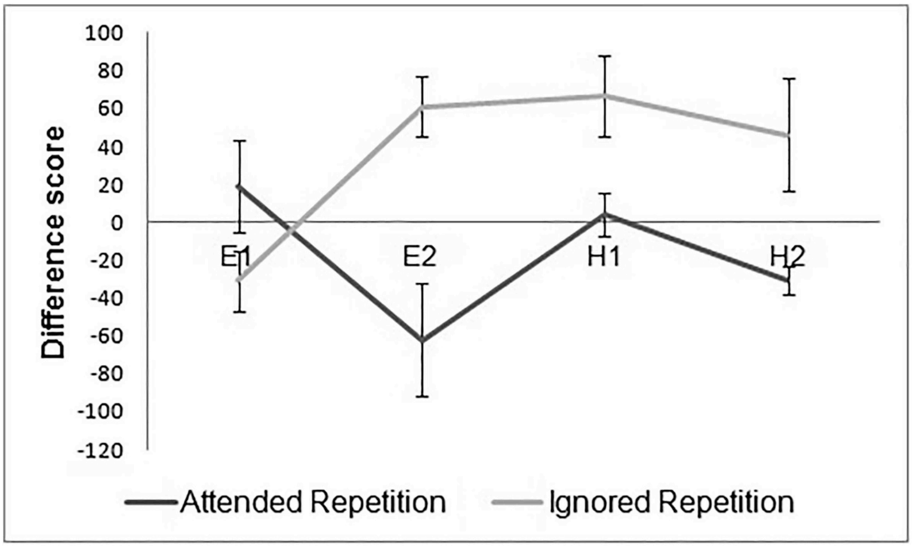

Fig. 2. Behavioural performance on the negative priming task with linguistic stimuli showing comparisons between monolongual-bilingual (H1; E1) and bilingual-bilingual (H2; E2) prime-probe combinations for both languages for attended repetition and ignored repetition condition..

.2.1. Language proficiency and inhibition effects

In the domain of speaking/understanding, there was a significant correlation between the total score of L2 proficiency and the inhibition effect in L2 for the monolingual-bilingual prime probe combination trials, r = 0.514, $p = 0.02$. The total score of L2 predicted 22.3% of the variance in performance on the negative priming task (R square = 0.264, adjusted R square = 0.223), and the model was significant, $F(1, 18) = 6.46, p = 0.02$. The total score of L1 did not significantly predict the performance on the linguistic version of the negative priming task. However, synonym task in L1 in the speaking/understanding domain, predicted performance on the negative priming task for L1 and accounted for 16.2% of the variance (R square = 0.206, adjusted R square = 0.162) and the model was significant, $F(1, 18) = 4.671, p = 0.044$.

In the domain of reading/writing, reading speed in L1 and reading fluency in L2 were correlated with the difference scores in L2 for the monolingual prime-probe combination trials. Both accounted for 21.2% of variance (R square = 0.295, adjusted R square = 0.212) and the model showed a trend of significance, $F\ (2, 17) = 3.55, p = 0.051$. On the other hand, reading comprehension in L1 significantly predicted the negative priming task performance in L1. There was a negative correlation between reading comprehension in L1 and attended repetition condition in L1 only for monolingual-bilingual combination trials. Reading comprehension accounted for 29.8% of variance (R square = 0.331, adjusted R square = 0.298) and the model was significant, $F\ (1, 18) = 6.88, p = 0.006$. In case of bilingual prime-probe combination trials, reading comprehension in L1 predicted 27.0% of variance (R square = 0.309, adjusted R square = 0.270) in the difference scores of both attended and ignored repetition conditions for L1 and the model was significant, $F\ (1, 18) = 8.042, p = 0.011$.

Thus, results based on regression analysis suggest that L2 proficiency for the speaking/understanding domain predicted performance on the linguistic negative priming task. In contrast, only task-specific relationship was observed between L1 proficiency (synonym task) and negative priming task performance. Since the negative priming task involved animacy judgement with words as stimuli, reading speed and reading comprehension emerged as significant predictors of performance on the negative priming task.

To sum up the findings of the experiment in Experiment 1, inhibitory control effects were evident in both languages when prime and probe trials had bilingual stimuli. L1 proficiency showed a task (reading comprehension) specific relationship, whereas L2 proficiency across domains, including both speaking/understanding and reading/writing skills, showed a significant correlation with performance on the negative priming task.

2. Experiment 2a: ERP correlates of the cross-linguistic negative priming effects in Hindi and English language

This study examined the ERP correlates of inhibitory control in Hindi-English bilingual adults by using comparable visual identity negative priming tasks with linguistic and nonlinguistic stimuli. The first experiment examined inhibition effects for lexical-semantic processing in L1 (Hindi) and L2 (English). Modulation of N200 amplitudes as a measure of inhibitory control and conflict monitoring was expected for both linguistic and nonlinguistic tasks. Since L1 has a stronger representation than L2, we expected to find the greater amplitude of the N200 component for the ignored repetition condition in L1 compared to L2. We also hypothesized higher amplitude of the N200 component (associated with inhibition effects) for the ignored repetition condition (as a measure of the carry-over effect of inhibition) compared to the control condition for nonlinguistic stimuli. Ignored repetition condition is a high monitoring condition given that one needs to attend to the target, which was a distractor and was ignored in the previous trial. The relationship between proficiency in L1 and L2, and changes in ERP amplitudes with respect to the negative priming effects was also examined. It was hypothesized that the amplitudes of the N200 component would be positively correlated with inhibition effect in L2 and nonlinguistic stimuli.

3.1. Method

3.1.1. Participants

Eighteen Hindi-English Bilingual adults in the age range of 18–26 years (Mean age = 22.66 years, SD = ± 2.5; 9 males and 9 females) participated in the study. The selection criteria were the same as described in the first study. Language history questionnaire and the test of language proficiency in Hindi and English were administered as described in the first study.

3.1. Stimuli and procedure

The identity negative priming task with overlapping linguistic stimuli was designed using the STIM2 software (Neuroscan Inc., Australia). The design was similar to the one described in the first study with a few modifications. The design of the experiment was modified for the timeline by providing a maximum time window of 1500 ms for response between two trials to avoid the overlap error in ERP. The control condition was also added to the current trial structure. Thus, there were three conditions in this experiment (960 trials): attended repetition (300 trials), ignored repetition (180 trials), and control condition (480 trials). The attended repetition and ignored repetition conditions were similar to the behavioural experiment conducted in the first study. The control condition consisted of a single word overlapped with a string of symbols like unfilled boxes (similar in size as the words), subtending at 2° at the centre of the screen. The monolingual prime-probe trials (H1/E1) were not retained in the current design to reduce the duration of the experiment and also because the issue of switching was addressed in the first study. The bilingual prime-probe trials and control trials only were considered for the current experiment.

The experiment began with a fixation point for 400 ms followed by a pair of overlapped words/words overlapped with a string of symbols for 300 ms, after which the response window stayed for 1500 ms within which the participant was required to respond.

Participants responded by pressing the response buttons, 1 for animate, and 2 for inanimate words using the response pad (Neuroscan EEG/ERP system) with four response buttons. Response keys were counterbalanced across participants. The experimental task and ERP recording procedure were explained to the participants. Participants were seated comfortably at a distance of 60 cm from the computer monitor in an isolated sound room. Participants were given instructions about the negative priming task and were asked not to blink or move while the stimuli were being presented. For each trial, the stimulus was presented at the centre of the screen. The entire procedure, including the preparation of the participant with the placement of the electrode cap, achieving the impedance, and conducting the experiment, took about 1 h 45 min.

3.1.3. EEG data acquisition and processing

Stimulus presentation was performed with STIM2 software (Neuroscan Inc., Australia), and responses were recorded using a response pad. The 64 electrode cap was positioned over the scalp according to the criteria of the international 10–20 system of placement of electrodes. Continuous EEG was recorded using the 64 channel EEG system (SCAN 4.3, Neuroscan Inc., Australia) referenced to the left and right mastoid bones. The horizontal EOG activity was recorded from two bipolar electrodes positioned on the outer canthi of both eyes. Vertical EOG activity was recorded from two bipolar electrode sites, above and below the right eye. The impedance at each electrode site was maintained below 5 kΩ. The raw EEG data recorded during the trials was digitized at 1000 Hz sampling rate. A 50 Hz notch filter was applied to remove noise due to the current line.

Raw EEG data were pre-processed using a band-pass filter (1–30 Hz). The filtered data was segmented into target-locked epochs of −100 ms–500 ms. The epochs were baseline corrected using the pre-stimulus interval (−100 to 0 ms). The muscle movement artifacts and ocular artifacts (exceeding 50 μV) were removed from single trials. Separate averaged waveforms for each condition were generated. ERP data yielded electrophysiological measurement for the attended repetition condition, ignored repetition condition as well as the control condition. Trials (at least 60 trials per condition after artifact rejection were averaged, taking an epoch of −100 to 500 ms. Separate averaged waveforms for each condition were generated. Negativity was observed predominantly at the frontal-central electrode site (FCZ) around 200–300 ms consistently for all the participants across conditions, more specifically between 240 and 260 ms for L1 and 260–280 ms for L2. Negativity was observed to be more in the anterior and central sites as compared to the posterior sites. The ERP waveforms showed a pre-stimulus dip between 0 and 50 ms consistently for all the participants, which could be due to the preparation for the upcoming target (linguistic stimuli are expected to result in activation suppression mechanisms in case of cross-linguistic stimuli).

3.2. Results

3.2.1. Behavioural results

All participants completed the cross-linguistic negative priming task. The mean accuracy across participants was 88.93%. A two-way ANOVA with 2 (language)*2 (priming condition) was performed. The effects were not statistically significant. Further analysis of slow (95th percentile) and fast (5th percentile) trials suggested that the inhibition effect in terms of the difference scores (i.e., the difference between the mean RTs of ignored repetition condition and control condition) showed contrasting results for both the languages. L1 (Hindi) showed greater inhibition effect as compared to L2 (English) for the fast trials, $t(17) = 3.982, p = 0.001$. Slow trials only showed a trend of significance, $t(17) = -1.908, p = 0.073$).

3.2.2. ERP results: N200 analysis (time window 200–300 ms)

ERP data were analysed comparing the mean amplitudes across conditions (AR, IR, and control) and languages (L1 and L2) as well as with difference waveforms (subtracting the mean amplitudes of control condition from those of attended repetition condition and ignored repetition condition). The visual inspection of the ERP waveforms showed an observable change in the waveform at the frontal central sites consistently across participants. Mean amplitudes were computed for the two languages and each of the conditions at the FCZ electrode site. A two way repeated measures ANOVA with 2 (language)* 2 (priming condition) design, was performed. Main effect of priming condition was significant, $F(1, 17) = 7.542, p = 0.014$. The mean amplitudes of the N200 component were larger for the ignored repetition condition as compared to the control condition. The main effect of language was not significant $F(1, 17) = 2.305, p = 0.147$. Interaction between language and priming condition was not significant, $F(1, 17) = 3.429$, $p = 0.082$. As the mean peak latency for both the languages is different, planned comparisons were performed to understand language-specific effects. Results showed that N200 amplitudes were enhanced for the ignored repetition condition as compared to the control condition for L1 Hindi, $t(17) = 2.65, p = 0.015$ and L2 English, $t(17) = 3.34, p = 0.003$) (see Fig. 3a & 3b). In addition, N200 amplitudes for the ignored repetition condition were larger for L1 as compared to L2, $t(17) = 2.903, p = 0.01$) (Fig. 4).

Latency analysis for the ignored repetition condition also showed a significant difference between the two languages, $t(17) = 3.747, p = 0.001$). Overall mean peak latency was 237 ms for Hindi and 267 ms for English across priming conditions. Mean amplitudes were computed for the difference waveforms (attended repetition minus control for facilitation effect and ignored repetition minus control for inhibition effect) of the N200 wave for Hindi and English language. Paired sample *t*-test results showed that the N200 amplitudes were higher for the inhibition effect as compared to the facilitation effect for L1 and L2, $t(17) = 2.938$, $p = 0.008$) and $t(17) = 2.178, p = 0.0042$ respectively. Moreover, the inhibition effect was found to be greater for L1 Hindi as compared to L2 English. Besides, a paired sample *t*-test was performed between ignored repetition condition and the control conditions for various anterior electrode sites. Left-sided frontal electrodes (F3, FC3, FC5 for L1 and F3, FC1, FP1, FPz for L2) showed inhibition effect for both L1 and L2, suggesting the involvement of frontal and prefrontal electrodes ($p < 0.05$).

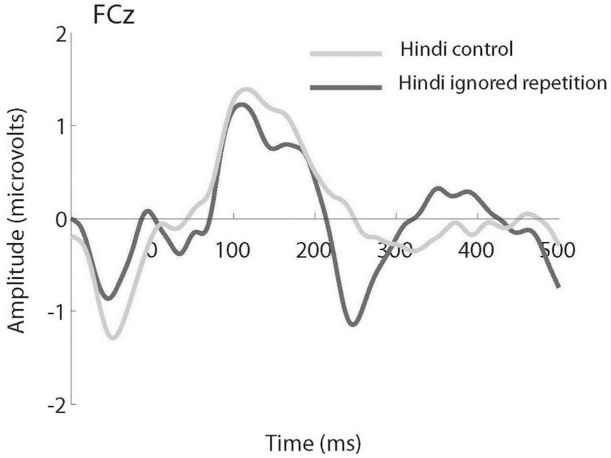

Fig. 3a. Grand averages of the ERPs elicited by control and ignored repetition condition for the L1 (Hindi language).

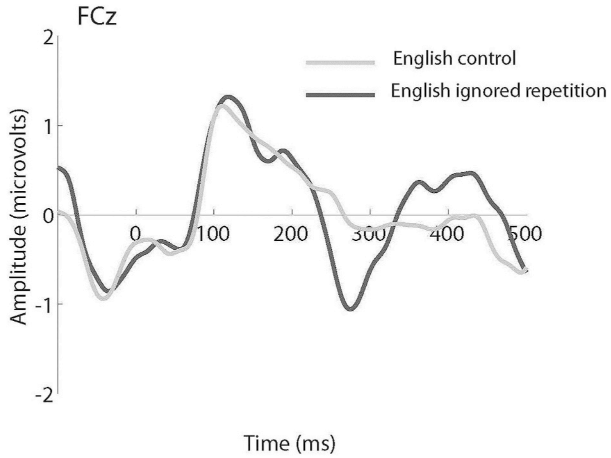

Fig. 3b. Grand averages of the ERPs elicited by control and ignored repetition condition for the L2 (English language).

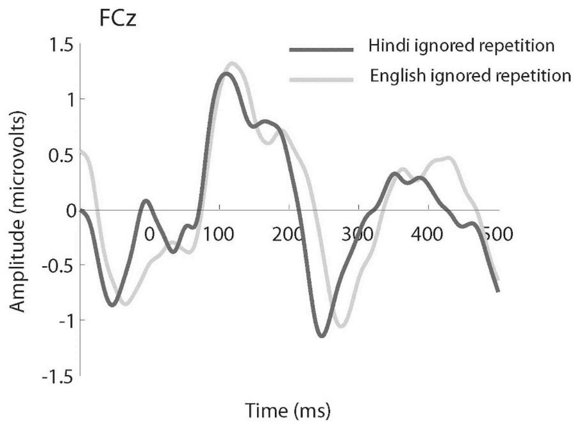

Fig. 4. Grand averages of the ERPs elicited by the ignored repetition condition for both the languages.

3.2.3. Language proficiency and negative priming effects (N200 amplitudes) for linguistic stimuli

The relationship between language proficiency and negative priming effects for changes in the latency and amplitudes of the N200 component was also examined. We examined if the difference in amplitudes between ignored repetition condition and control condition (as a measure of inhibition effect) was correlated with language proficiency scores of L1 and L2. Multiple regression analysis was performed by using the simultaneous method. In the domain of speaking/understanding, there was a significant correlation between the total scores of L2 and N2 amplitudes for the inhibition effect in L2, $r = 0.59$, $p = 0.004$. The total score of L2 predicted 32.6% of the variance in the N2 amplitudes. (R square = 0.35, adjusted R square = 0.32) and the model was significant, $F(1, 16) = 10.65$, $p = 0.004$. Similarly, the total score of L2 in the domain of reading and writing also predicted 44.8% of the variance in N2 amplitudes for the inhibition effect in L2 (R square = 0.475, adjusted R square = 0.448). The model was significant, $F(1, 16) = 17.20$, $p = 0.001$.

In the domain of speaking understanding, discourse analysis in L1 predicted 15.4% of the variance in the N2 amplitudes on ignored repetition condition for L1 (R square = 0.197, adjusted R square = 0.154) and model was significant ($F(1, 16) = 4.65$, $p = 0.044$). The total score in speaking/understanding or reading/writing domain was not able to predict inhibition effects in L1.

To sum up the findings based on experiment 2a, overall inhibition effect showed larger amplitudes for both L1 and L2 compared to the facilitation effect. Similarly, the ERP data showed greater amplitude for the N200 component (as a measure of inhibition) for the ignored repetition condition for L1 compared to L2 and control condition. Also, the mean peak latency of the N200 component was earlier for L1 than L2 due to the strong representation for L1. Interestingly, overall L2 proficiency and task-specific L1 proficiency predicted N200 amplitudes for the inhibition effect in L2 and L1, respectively.

3. Experiment 2b: nonlinguistic negative priming effects on N200 amplitudes among bilingual adults

The purpose of the current experiment was to demonstrate negative priming effects among bilinguals for changes in the amplitudes of the N2 component on a nonlinguistic negative priming task. We also examined the relationship between L1 and L2 proficiency with the changes in ERP amplitudes to demonstrate the relationship between proficiency and general-purpose inhibitory control.

4.1. Method

4.1.1. Participants

Eighteen Hindi-English bilingual adults in the age range of 18–26 years participated in the experiment (Mean age: 22.66 years SD = ± 2.2; 9 males and 9 females). The selection criteria for participation were similar to the first study. Participants in both the experiments (2a and 2b) were matched on L1 and L2 proficiency. Language history questionnaire and test of language proficiency in Hindi and English were administered to all the participants.

4.1.2. Stimuli and procedure

The identity negative priming task with nonlinguistic stimuli, including overlapping line drawings of animate and inanimate objects, was employed while recording EEG/ERP. The trial began with a fixation point for 400 ms, followed by the overlapping line drawings in shades of light gray and dark gray. The pictures were selected from the IPNP database (Abbate & LaChapelle, 1984). A total of 130 images were taken and were rated by 10 high proficient Hindi-English bilinguals at the University of Allahabad. Pictures were rated on familiarity and frequency of use of picture names on a 0–5 rating scale. Fifty images were selected, consisting of an equal number of animate and inanimate categories (Mean rating = 4.17, SD = 0.63). With these images, 620 overlapping stimuli were created in different combinations. Prime and probe trials were carefully designed so that there were no phonological or semantic overlaps within a trial as well as between two trials.

The participants were required to identify the target picture as animate or inanimate and press the corresponding keys ("1" for animate and "2" for inanimate) using the four-button response pad. Trials were pseudo-randomized to maintain an equal number of prime probe combination trials. There were four blocks and with three rest pauses for 1 min, 3 min and 1 min respectively after every 240 trials. There were three conditions in this experiment, similar to the linguistic negative priming task: attended repetition, ignored repetition, and control condition. The control condition consisted of trials in which stimuli did not repeat between the prime and probe trial and thus contained four different animate/inanimate pictures in both trials. The behavioural data in terms of reaction times was analysed similar to the analysis performed in experiment 1, and the ERP waveform analysis was performed using similar data processing and analytical procedures described in experiment 2a.

3.2. Results

3.2.1. Behavioural results

A paired-samples *t*-test was performed comparing the mean reaction times of the control condition and ignored repetition condition. There was a significant difference between the two conditions, $t(17) = -3.743$, $p = 0.002$, indicating a significant negative priming effect.

4.2.2. EEG/ERP results

Raw EEG data were pre-processed using similar parameters as described for experiment 1 of the second study. ERP amplitudes were averaged across trials (at least 60 trials per condition after artifact rejection were analysed) by taking an epoch of −100 ms–500 ms. ERP waveforms within an epoch of 200–300 ms at the FCZ electrode site were analysed to derive the mean amplitudes for ignored repetition condition and control condition (see Fig. 5). A paired samples *t*-test showed a significant difference

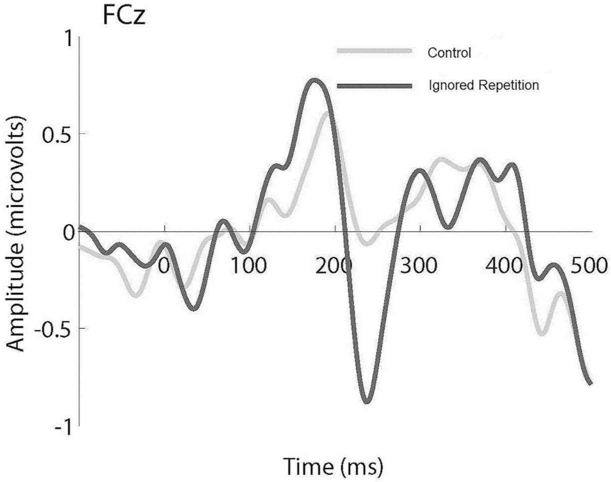

Fig. 5. Grand averages of the ERPs elicited by control and ignored repetition condition for the nonlinguistic stimuli.

between the mean amplitudes of the two conditions, $t(17) = 2.786$, $p = 0.013$. Mean amplitudes of the N200 component were larger for the ignored repetition condition as compared to the control condition suggesting a significant negative priming effect.

4.2.3. Language proficiency and negative priming effects for nonlinguistic stimuli

It was interesting to find that the total score on L1 in speaking/understanding domain predicted 25.3% of the variance in the mean amplitudes of the N200 component for nonlinguistic stimuli and model was significant, $F\,(1,17) = 5.40$ $p = 0.034$. In contrast, task-specific L2 proficiency for words per minute in the L2 reading task was able to predict 26.4% of the variance in the mean amplitudes of the N200 component for nonlinguistic stimuli and model was significant $F\,(1,17) = 5.74$, $p = 0.029$.

To summarize, results based on experiment 2 b showed a significant negative priming effect for nonlinguistic stimuli, also supported with greater mean amplitude for ignored repetition condition. Overall L1 proficiency and task-specific L2 proficiency predicted the mean amplitudes for the N200 component for nonlinguistic stimuli.

4. Discussion

The current study examined inhibition as a component process of cognitive control among Hindi-English bilinguals. The visual identity negative priming paradigm with linguistic and non-linguistic stimuli provided a comparable design to investigate bilingual language control and general-purpose cognitive control. We also examined the relationship between language proficiency and bilingual language control and GPCC. Proficiency in L1 and L2 shows a dynamic relationship with the different domains of cognitive control (i.e., through linguistic and nonlinguistic inhibitory control tasks). In addition, findings also suggest that various aspects of language proficiency across language domains are correlated with inhibition mechanisms and are also determined by the task context.

Based on our behavioural (study 1) and ERP results (study 2), we find that the inhibitory control effects were evident in both languages. The behavioural experiment also showed that these effects were modulated by the weight of a particular language in the given trial (i.e., for L1 HH > HE). ERP results showed significant modulations of the N200 amplitudes at the frontal central electrode site as a function of demands on inhibitory control and language. Modulations in the N2 amplitudes at the FCZ electrode site is an electrophysiological correlate of inhibition and conflict monitoring detected in the anterior cingulate cortex (ACC) (Nieuwenhuis & Yeung, 2003). Moreover, activity in the ACC areas is often associated with the effect of bilingual experience on cognitive control (Abutalebi et al., 2012). The performance of bilinguals, as well as monolinguals on a conflict monitoring task, is correlated with modulations in the ACC sulcation (Cachia et al., 2017). The current study also finds a significant correlation between L1/L2 proficiency and the N200 amplitudes at the FCZ electrode site. In addition, our results indicate many commonalities as well as differences between the bilingual language control and general-purpose cognitive control mechanisms.

5.1. Inhibition as a component process of cognitive control in bilinguals

According to Green's inhibitory control model (Green, 1998), the role of inhibition effect is based on the dominance of a particular language. The behavioural results (study 1) suggest that the weight or load of a specific language (i.e., HH > HE) for the prime and probe combination was a crucial factor in the modulation of the control mechanism. We found that the negative priming effect on the current trial was significant only when the previous trial was a bilingual trial (HE) and not for monolingual trial. Bilingual trials can be considered as trials that keep both the languages activated thus, resulting in the need for the inhibitory control mechanism. Greater activation in the bilingual trial in comparison to a monolingual trial was also evident in the German-French bilingual study in the left caudate and anterior cingulate circuits (Abutalebi et al., 2008). Monolingual trials put a low load on the language control system resulting in lesser involvement of the control circuits. The behavioural data established the linguistic version of identity negative priming paradigm and also provided evidence of sustained inhibitory effects on the current trial in the context of bilingual trials only (i.e., the previous trial being a bilingual trial).

We also find a more significant inhibition effect for L1 (Hindi) as compared to L2 (English), which is in accordance with Green's inhibitory control model (Green, 1998), suggesting that dominant language shows greater inhibitory control. Inhibitory control among Hindi-English bilinguals was further studied by using ERP with both linguistic and nonlinguistic versions of the identity negative priming task. The ERP data suggested that inhibition effects were present in both versions of the experiment in the form of N200 for both languages as well as nonlinguistic stimuli. There was no significant effect of animacy or switching on the cross-language negative priming effect. We observed a significant difference for the N200 across priming conditions supporting the inhibitory control hypothesis of the negative priming paradigm which is in accordance with the previous studies (Neill & Valdes, 1992; Driver & Tipper, 1989; Heil, Osman, Wiegelmann, Rolke, B & Henninghausen, 2000; Nieuwenhuis, Yeung, Van den Wildenberg, & Ridderinkhof, 2003; Enriquez-Geppert, Konrad, Pantev, & Huster, 2010). However, these negative priming results based on previous studies are predominantly with nonlinguistic stimuli.

In the linguistic version of the ERP- negative priming task, language-based differences in terms of higher mean amplitudes as well as earlier latency of N200 for L1 (Hindi) is due to the stronger representation of L1. Although effects were also present for L2 but with lower amplitudes and increased mean peak latency. The latency and amplitude differences between the languages are dependent on language-related factors such as language proficiency, use, etc.

Moreover, comparison of linguistic and nonlinguistic inhibition effects showed an increasing order of amplitudes of the N200 component across the three stimulus types (L1 > L2 > nonlinguistic) and mean peak latency of the N200 component was found to be earlier for L1 than L2 and nonlinguistic stimuli for the ignored repetition condition. The difference in the mean peak latencies between nonlinguistic and linguistic stimuli is due to the faster semantic categorization for pictures as compared to the words (Theios & Amrhein, 1989; Yum, Holcomb, & Grainger, 2011). The amplitude differences are due to the stronger conceptual and perceptual processing of picture stimuli as compared to words (Stenberg, 2006; i.e., the picture superiority effect). Furthermore, the link between the L1 and conceptual representation is stronger than that of L2, resulting in the amplitude and latency differences between the two languages. However, this link between lexical and conceptual representation is also influenced by the level of language proficiency.

5.2. *Language proficiency predicts bilingual language control and general-purpose cognitive control*

Language proficiency (both L1 and L2) showed a complex and dynamic relationship with inhibitory control. In line with the current trend (Anthony & Blumenfeld, 2018; Incera & McLennan, 2018), our study also provides evidence not only for the relationship between L1/L2 language proficiency and inhibitory control but also considered language proficiency as a continuous variable. Results related to L2 proficiency are in line with a previous study that has shown the effect of L2 proficiency on executive functions by comparing bilinguals with high and low proficiency based on a particular language skill using measures like PPVT for proficiency (Bialystok, Craik, Green, & Gollan, 2009). This is also consistent with another study using nonlinguistic Simon task, Simon switching, and working memory tasks with Cantonese–English bilinguals showing a significant relationship between proficiency and attentional control (Tse & Altarriba, 2014). Few studies on the effect of L2 proficiency on oculomotor control have reported better monitoring and interference control among high proficient Hindi-English bilinguals (Singh & Mishra, 2012). In addition, one of the recent studies on Hindi-English bilinguals has also shown the effect of second language proficiency on proactive inhibitory control with reduced proactive inhibition cost in high proficiency bilinguals in a nonlinguistic cued go/no-go task in oculomotor domain (Singh & Kar, 2018). In the current study, L2 proficiency across language domains predicted the second language inhibitory control, whereas, synonym task and reading comprehension task in L1 predicted the first language inhibitory control. This task-specific predictor model for the first language was also observed in the linguistic version of the ERP study. On the other hand, the total score on L1 proficiency and task-specific (discourse analysis) second language proficiency predicted general-purpose control (nonlinguistic negative priming effect). Tse and Altarriba (2012) have demonstrated a significant effect of L1 and L2 proficiency on conflict resolution and goal maintenance in a Stroop task. Both L1 and L2 proficiencies were found to be associated with a shift in reaction time distributions suggesting that performance on the Stroop task could be modulated by proficiency. However, Tse and Altarriba (2012) did not look at the differences in the relationship between L1 vs. L2 proficiency and cognitive control, as observed in the current study.

L1 in the current context is a naturally learned and highly used language and contributes towards a domain-general influence of L1 on cognitive control. Whereas the second language is learned in a structured setting through formal instruction and thus contributes to domain-specific impact on the cognitive control construct (i.e., bilingual language control). These results are unique in terms of addressing different facets of the relationship between language proficiency as a measure of bilingualism and cognitive control. Previous data on bilingual advantage in cognitive control, have predominantly described the bilingual advantage based on L2 proficiency only (Kar, Khare, & Dash, 2011; Khare, Verma, Kar, Srinivasan, & Brysbaert, 2013; Pivneva, Palmer, & Titone, 2012; Singh & Kar, 2018; Singh & Mishra, 2012), whereas our results highlight the differential involvement of both L1 and L2 proficiency. This is supported by the findings from our previous study (Dash & Kar., 2012), which showed that clustering of language skills (measured on the basis of the performance on language proficiency tasks in the domain of speaking/understanding and reading/writing domains) is more cohesive for L2 as compared to L1 (Dash & Kar, 2012). Since the organization of language skills itself is not similar for both L1 and L2, we find different patterns of relationship between language proficiency as a measure of the degree of bilingualism and the cognitive control construct.

In contrast to the previously used tasks (confrontation naming, reading comprehension, self-rating) of language proficiency, we find a significant relationship between discourse analysis (L1) and bilingual language control. Discourse skills are higher-level language skills, which require language control. Thus, overall expertise in the second language, along with the discourse skills of L1 are crucial for the bilingual language control. The general-purpose cognitive control is a domain-general process influenced by the overall language skills of the first language along with the task-specific (reading skills) influence from the second language. Thus, bilingual language proficiency in both L1 and L2 across domains of speaking/understanding/reading/writing predicts control mechanisms rather than just the knowledge of the two languages.

5. Conclusion

We examined the relationship between L1 and L2 proficiency as a measure of bilingualism and inhibitory control in the context of linguistic and nonlinguistic stimuli using the negative priming paradigm. This paradigm examines inhibitory control and has not been used much to look at the interaction between bilingualism and cognitive control. In addition, there are very few studies on language proficiency as a measure of bilingualism and its relationship with control mechanisms involved in language control or GPCC. The findings of the current study provide insight into the theoretical debate of whether bilingual control is subsidiary to general-purpose cognitive control. It has been proposed that bilingual language control is not completely subsidiary to the general-purpose cognitive control system, and our findings also support this account. In the current study, we examined inhibitory control in L1 Hindi, L2 English, and nonlinguistic stimuli. The presence of N200 for linguistic stimuli in both languages, as well as nonlinguistic stimuli is suggestive of the commonalities in the underlying cognitive control mechanism irrespective of the stimulus type. However, the differences in mean amplitudes (L1 > L2 > nonlinguistic) and mean peak latency of the N200 waveform (L1 < L2 < non-linguistic) across linguistic and nonlinguistic stimuli indicate differences in the degree of involvement of the inhibitory control mechanisms associated with bilingual language control and general-purpose cognitive control. In addition, L1 and L2 proficiency showed contrasting effects for inhibitory control for linguistic and nonlinguistic stimuli. Our findings suggest that bilingual language control is related to the overall L2 proficiency and task-specific L1 proficiency. On the other hand, general-purpose cognitive control is associated with the overall L1 proficiency and task-specific L2 proficiency.

CRediT authorship contribution statement

Bhoomika R. Kar: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing - review & editing.

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