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# Looking Without Knowing: Evidence for Language-Mediated Eye Movements to Masked Words in Hindi-English Bilinguals

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**Abstract:** Cross-linguistic activation has been frequently demonstrated in bilinguals through eye movements using the visual world paradigm. In this study, we explored if such activations could operate below thresholds of awareness, at least in the visual modality. Participants listened to a spoken word in Hindi or English and viewed a display containing masked printed words. One of the printed words was a phonological cohort of the translation equivalent of the spoken word (TE cohort). Previous studies using this paradigm with clearly visible words on a similar sample have demonstrated robust activation of TE cohorts. We tracked eye movements to a blank screen where the masked written words had appeared accompanied by spoken words. Analyses of fixation proportions and dwell times revealed that participants looked more often and for longer duration at quadrants that contained the TE cohorts compared to distractors. This is one of the few studies to show that cross-linguistic activation occurs even with masked visual information. We discuss the implications for bilingual parallel activation and unconscious processing of habitual visual information.

**Keywords:** parallel activation; cross-linguistic activation; bilingual; unconscious; masked; translation; visual world

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## 1. Introduction

One of the most fascinating aspects of the bilingual mind is seen in cross-language activation of lexical items. It is now well-known that both languages of a bilingual are active to some degree during everyday activities (Kroll & Ma, 2017; Schwartz & Kroll, 2006). Evidence for this has been found across a range of tasks such as listening (Spivey & Marian, 1999), reading (Dijkstra et al., 1999, 2000) and speaking (Colomé, 2001; Jared & Kroll, 2001; Jared & Szucs, 2002). It is seen in bilinguals who are highly proficient in their second language (L2), in L2 learners (Blumenfeld & Marian, 2007; Van Hell & Dijkstra, 2002), across language pairs that are markedly different from each other (Mishra & Singh, 2014, 2016) and even across modalities (Shook & Marian, 2012). Although most researchers think that such activations are spontaneous, it is still not known to what extent they are automatic. Further, many bilinguals are also biliterate. They can read and write in two languages. Important models in psycholinguistics of word processing have linked lexical activation during spoken words to orthographic activation (Dijkstra & Van Heuven, 2002; Shook & Marian, 2013). When bilinguals hear a word in any language, they also activate the orthographic forms of these words spontaneously. Building on previous observations, this study further explored if bilinguals indeed activate translation equivalents of spoken words in orthographic forms during listening and if this can proceed with minimal conscious awareness. We used the visual world paradigm with eye-tracking and presented spoken words with masked written words.

The visual world paradigm has been particularly useful in studying parallel activation (see Huettig et al., 2011 for a review). In this paradigm, listeners are given linguistic input (spoken words or sentences) while they view a display containing pictures or words. It is often observed that individuals make eye movements to objects in the display that are in some way related to the audio input. These eye movements reflect the integration of visual and linguistic information. The relationship between the elements in the display and the linguistic input can be manipulated to study various aspects of language processing. For instance, bilinguals often preferentially look at pictures or words whose names in one language have a phonological overlap with a spoken word in another language (Marian & Spivey, 2003). This is taken as evidence for cross-linguistic activation. Early studies by Marian and colleagues (Shook & Marian, 2012) demonstrated that Russian–English bilinguals in the USA activate the translation equivalents of the spoken word and preferentially look at pictures or words whose names are phonologically similar to the translation word (Shook & Marian, 2019).

The Revised Hierarchical Model (RHM, Kroll & Stewart, 1994) explained why certain bilinguals need to translate between their languages from a developmental perspective. Bilinguals who learn their second language later and have low proficiency have a higher need to translate. This is because of weak conceptual associations between L2 words and their meanings, requiring the activation of L1 translations to access meaning. Consequently, translating from L2 to L1 is typically faster and easier than translating from L1 to L2 for L2 learners. Supporting this, studies have reported stronger translation activation for L2 spoken words compared to L1 (Blumenfeld & Marian, 2007; Mishra & Singh, 2016). However, faster and more automatic translation from L1 to L2 has also been observed in studies with high-L2-proficiency participants (Prasad & Mishra, 2021). According to the Revised Hierarchical Model (RHM), the translation pathway is primarily active in less proficient L2 learners. As L2 proficiency increases, it may enable more direct access to the meaning of L2 words, thereby weakening the lexical connection between L2 and L1 words and suggesting a complex interplay between proficiency and translation activation in the visual world paradigm. Translation activation in the visual world paradigm has also been shown across different language pairs that do not share form or orthography, in both high- and low-proficiency speakers (Mishra & Singh, 2014, 2016; Singh & Mishra, 2015; Wang et al., 2017). For instance, Mishra and colleagues have repeatedly shown that when Hindi–English bilinguals listen to the word *monkey*, they activate the translation word in Hindi *bandar* and words that sound similar to *bandar*, such as *bandook* (gun). This is inferred from increased looks to the picture of a *gun*/*bandook* when participants listen to the word *monkey* (Mishra & Singh, 2016).

The bilingual mind has evolved to dynamically represent multiple symbolic structures that are linked conceptually or by form. For example, bimodal bilinguals regularly activate both signs and their spoken/written language translations during language processing (Villameriel et al., 2022). Thus, expertise and proficiency lead to spontaneous activations of any two symbolic systems—not necessarily linguistic. Data from bimodal bilinguals, obtained through the visual world paradigm, are an important demonstration of the very volatile nature of the conceptual representation in the bilingual brain. The rapid spread of activation from the input word to many other words in both languages, in many different formats, influences eye movements, behavior that is linked to mechanisms of cognition. These automatic activations are susceptible to triggers that are both internal or external.

According to the taxonomy developed by Moors and De Houwer (2006), a process is considered automatic if (1) it is fast, efficient and requires little to no cognitive effort; (2) it runs unintentionally; (3) it is unconscious; (4) it is overlearned. The cross-language activation data from visual world paradigms can be considered automatic as they are spontaneous and task-irrelevant. There is little experimental evidence showing bilinguals restricting such activations to one language. Thierry and colleagues have observed parallel activation of both languages even in contexts where only one language is used or when there is no explicit linguistic task, suggesting that these activations are automatic (Thierry & Wu, 2007; Wu & Thierry, 2012). In a seminal study, Thierry and Wu (2007) administered a semantic relatedness task to Chinese–English bilinguals. Participants were presented with English word pairs (train–ham) and asked to decide if the words were related to each other. In half of the trials, the two words shared a character when translated to Chinese (train—Huo Che—and ham—Huo Tui). Brain potentials showed reduced N400 on such trials where the translation words in Chinese shared a character. This was interpreted as evidence that the Chinese–English bilinguals unconsciously translated the English words into Chinese, even though the entire experiment was administered only in English. In sum, the research reviewed so far demonstrates that varieties of bilinguals with many different pairs of languages from different cultures translate words from one language to the other, even when the language context necessitates the use of only one language. However, most studies in this domain have only used spoken words or pictures to track this. Since bilingual readers also activate orthographic forms of spoken words in both languages (Huettig & McQueen, 2007), we aimed to further demonstrate that even this mechanism is spontaneous.

The unique nature of the language pairs used in this study is also worth mentioning. Many visual world studies have been conducted on bilinguals whose two languages have cognates (e.g., Dutch–English, Spanish–English), while Hindi and English do not share any orthography or phonology. Most educated bilinguals in India learn to use Hindi and English from an early age. Most also know how to write in these two languages. Therefore, translating between these languages comes naturally to such bilinguals. Most importantly, in everyday situations, both languages are used alternatively for communication. What is not empirically known is if such bilinguals also unconsciously activate the orthography of words in both languages during listening or reading in one language. Apart from exploiting the spontaneous nature of cross-linguistic activation in bilinguals in everyday language use, we also used the popular 'blank screen' paradigm version of the visual world. Altmann and colleagues first used it to demonstrate that oculomotor activations are possible for verbal input in the absence of corresponding visual objects (Altmann, 2004). Spivey and Geng (2001) also provided evidence of eye movements to nothing in other experimental contexts. The essential mechanism behind such eye movements lies in visual indexing. People associate spatial locations where objects might have been and look there even when the objects are no longer present at those locations. For example, most people will look 'up' when they hear the spoken word 'fan', which is the likely place for a fan in typical situations. In this experiment, we use the blank screen paradigm to track eye movements to masked printed words.

*Current Study*

Presenting a task in a single-language context (Thierry & Wu, 2007) is one efficient way of discouraging explicit activation of the second language and thereby demonstrating the unintentional and unconscious nature of cross-linguistic activation. Another method—explored in this study—is to mask the visual information from conscious awareness. The visual world paradigm is also especially suited to probe unconscious processing because eye movements—which are the key measures in the visual world paradigm—provide a direct window into mental events. Eye movements are a fast response system and can capture short-lived effects. Fixation data analyzed in visual world studies provide a dynamic overview of the process through which activations unfold at a millisecond level of precision and can provide richer information than a single button press.

To examine if cross-linguistic activation is seen with limited conscious awareness, we adapted and modified the design used by Mishra and Singh (2014) and Prasad and Mishra (2021). In both these studies, Hindi–English bilinguals listened to utterances in one language (English or Hindi) and viewed a display consisting of four printed words. One of the words was a translation equivalent (TE) cohort of the critical spoken word and the remaining three words were unrelated distractors. This is a variation of the standard visual world paradigm with line drawings. The printed version of the paradigm was developed to probe orthographic activations triggered by auditory input (Huettig & McQueen, 2007; Mcqueen & Viebahn, 2007). This method has been used to probe different aspects of language processing such as phonological and translation activation as well as the role of language proficiency (Huettig et al., 2011; Shen et al., 2018; Veivo et al., 2016, 2018). It is typically seen that, just like in the studies with line drawings, participants preferentially look at the TE cohorts more often than the unrelated distractors. This indicates robust activation of cross-linguistic orthographic information in bilinguals, which then guides eye movements in the visual display. We chose this design because it is easier to manipulate conscious awareness of words than line drawings.

There is a long history of using backward and/or forward masks in the psycholinguistics literature to suppress conscious awareness of critical stimuli (Forster, 1998). In such studies, a prime word (e.g., table) is presented for a short duration, followed or preceded by masks. It is often seen that the prime word influences responses to the target (e.g., chair) even when participants are not consciously aware of the prime word. We used this methodology of rendering words nearly invisible through visual masking in the design of Mishra and Singh (2014). The visual world display with the printed words was shown for 100 ms. The display was preceded and followed by a display presented for 150 ms containing "####" symbols at the center of each quadrant. These displays served as forward and backward masks for the visual world display. Next, the spoken input was presented while the participants viewed a blank screen for 3000 ms. Note that this is similar to visual world studies that offer a preview of the display before the spoken input is presented (Huettig & McQueen, 2007). We decided against presenting the spoken word and the visual world display simultaneously. This is because it typically takes a few hundred milliseconds to process audio input, by which time the visual world display would have disappeared owing to the short presentation times. Instead, we presented the audio after the critical display, accompanied by a blank screen.

We hypothesized that participants would index the locations with the objects presented at those locations. The spoken word input would then guide eye movements to the related locations due to cross-linguistic activation of the related words. Due to this, we predicted a greater proportion of fixations and higher dwell time for the TE cohort compared to the distractors. We also wanted to explore the role of language proficiency and the degree of bilingualism on the strength of unconscious parallel activations. Several studies have shown that second language proficiency modulates the magnitude and time course of cross-linguistic activation (Blumenfeld & Marian, 2007; Van Hell & Tanner, 2012). Several variables—such as the age of acquisition of the second language, medium of instruction during schooling, the extent to which the second language is used in the home and outside environment over the years—influence the degree of second language proficiency in bilinguals (Grosjean & Li, 2013). In particular, the age at which the second language is acquired is an important variable in bilingualism, leading to the distinction between early and late bilinguals (Grosjean & Li, 2013). In this study, we recruited participants who had acquired English at an early age to ensure that they would be highly proficient in English. We administered the Language and Social Background Questionnaire (LSBQ, Anderson et al., 2018), which is a comprehensive questionnaire assessing the degree of language use across different social contexts and self-reported proficiency. Our objective was to examine if the degree of bilingualism and self-reported proficiency in the second language correlate with the degree of cross-linguistic activation.

## 2. Materials and Methods

Fifty-eight Hindi (L1)–English (L2) bilinguals (17 females, mean age = 24.32 years, SD = 2.48) from the University of Hyderabad participated in this study. The sample size was estimated based on Prasad and Mishra (2021, Experiment 1) and Mishra and Singh (2014), which are the only two studies (to our knowledge) using the visual world eye-tracking paradigm with Hindi–English bilinguals in India. Prasad and Mishra had a sample size of 19 and Mishra and Singh had a sample size of 40. The effect sizes for these studies were 0.26 and 0.61, respectively. Using G Power 3.1 for linear multiple regression with these effect sizes, alpha set to 0.05, number of predictors set as 2 (for the effect of language and TE vs. distractor cohort), and the desired power of 0.8, the estimated sample size ranged between 20 and 41, respectively. We decided on a sample size considerably higher than 40 because the current study involved the use of masked words. All participants were native Hindi speakers and the mean age of acquisition of English was around 5.7 years (SD = 2.6). The language background information of the participants was collected using WordORnot (mean score = 52.9, SD = 13.4), semantic fluency (mean score L1 = 12.8, SD = 2.2; mean score L2 = 12.2, SD = 3.1) and the Language and Social Background Questionnaire (LSBQ). Written consent was obtained from all the participants for their participation. The Institutional Ethics Committee of the University approved this study.

### 2.1. Stimuli

The stimuli used in the study were taken from the previous studies of the authors (Mishra & Singh, 2014; Prasad & Mishra, 2021). The stimuli for each trial included four written words, from which one word was the TE cohort of the spoken word and the other three words were unrelated distractors. When the spoken word was in L1, the written words were in L2 and vice versa. For instance, if the spoken word was the L1 word मोर/Mor (Peacock in L2), the word peanut was presented on the screen as the TE cohort of the spoken word along with three other L2 distractor words unrelated to the spoken word or the TE cohort. The spoken words were recorded using the software “Audacity” by a male native speaker of Hindi (age = 29 years, age of acquisition of English = 5.5 years). The mean duration of the spoken words in L1 and L2 was 413 ms and 495 ms, respectively. All the word stimuli were rated on translation agreement and phonological similarity between the translation word and the TE cohort. Ratings were also obtained on the phonological and semantic similarity between the translation word and the four printed words for both language directions. The phonological similarity between the TE cohort and the translation word was significantly higher (L1–L2: M = 4.7, SD = 0.2, L2–L1: M = 4.44, SD = 0.62) compared to the similarity between the TE cohort and the distractors (L1–L2: M = 1, SD = 0.002, L2–L1: M = 1.15, SD = 0.31). Similarly, there was low semantic overlap between the translation word and the TE cohort (L1–L2: M = 1.05, SD = 0.11, L2–L1: M = 1.22, SD = 0.34). The semantic overlap between the translation word and the distractors was also low (L1–L2: M = 1.02, SD = 0.05, L2–L1: M = 1.18, SD = 0.28). More details on the rating procedure can be found in Prasad and Mishra (2021).

*2.2. Procedure*

The experiment started with a 9-point calibration on a 14-inch monitor with a screen resolution of 1024 px*768 px. The data were recorded using an Eyelink 1000 eye-tracking system with a sampling rate of 1000 Hz (Desktop mount model, SR Research Ltd., Kanata, ON, Canada) using a chin-rest to stabilize the head. Each trial began with a fixation cross (1o by 1o) placed at the center of the screen against a grey background (Figure 1). The screen was presented until the participants made a stable fixation for 1000 ms. Next, a display with four written words in L2 or L1 (TE cohort and 3 unrelated distractors) was presented for 100 ms. Just before and after the presentation of the written words, forward and backward masks (####) were presented for 150 ms at each of the word locations to mask the words. Following this, a spoken word was presented either in L1 or L2 along with a blank screen for 3000 ms. The spoken word was in the opposite language of the printed words in every trial. In 20% of the trials, the participants were presented with a written word following the blank screen and were asked to report whether they had seen this written word on the previous display screen by pressing the right or left shift keys. In half of the trials, the expected answer was "Yes". In the other half, the answer was "No" because a new word which was not previously seen on the display was presented. The mapping between yes/no and left-shift/right-shift keys was counterbalanced across participants. There were a total of 150 trials, out of which L1 spoken words were presented in a block of 75 trials and L2 spoken words in another block of 75 trials. The order of presentation of the language blocks was randomized. There was a practice session of 18 trials at the beginning of the experiment. The participants were informed that they would hear an audio clip while viewing four symbols or words on the screen. They were also told that, in some trials, a question related to one of the words would appear, and their task was to respond to the question. Importantly, they were not informed of any relationship between the printed words and the audio.

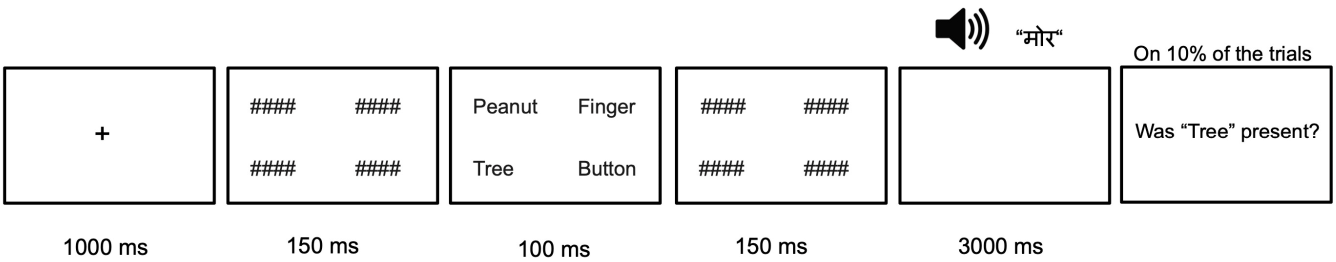


**Figure 1.** The sequence of events on a sample trial. This is an example of a trial with a Hindi (L1) spoken word.

After the main experiment, the participants performed a visibility task to assess the level of awareness of the masked words. The sequence of events was the same except for the final screen. Following the presentation of the spoken word, four written words were shown again. For each word, the participants were instructed to indicate if the same or different word was present at that location in the previous masked display by clicking the left (SAME)/right (DIFFERENT) mouse button. A total of 160 trials were administered, which consisted of 150 experimental trials and 10 practice trials.

*2.3. Language Measures*

WordORnot, an online vocabulary test (Center for Reading Research, Ghent University), was administered to test the proficiency of the participants in English. The test required the participants to judge a string of letters in English as "word" or "not-a-word". The participants had an average score of 53% (SD = 13), which was measured as the difference between the percentage of correct and incorrect responses. The participants also completed the semantic fluency test in both L1 and L2. It required participants to produce as many items as they could of four semantic categories—"animals", "birds", vegetables" and "fruits"—within 1 min for each category. Two categories were assigned for each language. This assignment was counterbalanced across participants. The semantic fluency score for each language was calculated by averaging the number of words produced per language. There was no difference between L1 and L2 semantic fluency scores, with t = 1.412 and $p = 0.163$.

Participants also completed the Language and Social Background Questionnaire (LSBQ, Anderson et al., 2018), which provides a comprehensive overview of language usage, exposure and self-reported proficiency. A composite score of language proficiency was calculated for each participant based on Anderson et al. (2018). Z-scores of 43 variables from the LSBQ were taken and summed together to calculate a composite value of English proficiency (EP), non-English home use and proficiency (NE-HUP) and non-English social use (NE-S). Z-scores take into account the variability across subjects. A weighted sum of these three variables (i.e., 0.33* NE-HUP + 0.3* NE-S + (0.11* EP) gave the bilingualism composite score (BCS), which signifies the degree of bilingualism of the participant. The weights were calculated based on a factor analyses by Anderson et al. (2018). The average BCS score was $2.8 \times 10^{-16}$ with a standard deviation of 3.69. The mean value was close to 0 as the composite scores are a linear combination of z-scores. Further, EP was given less weightage than the other variables based on the argument that social use of a non-English language is a critical factor and that English proficiency should not dominate the assessment of bilingualism as suggested by Anderson et al. (2018). In addition to the composite score derived from LSBQ, we also calculated an L2 composite score which takes into account both self-reported measures of proficiency and objective performance on a vocabulary test and semantic fluency test (Ma et al., 2017; McMurray et al., 2010). Many of the previous studies from our lab have reported these scores for similar bilingual samples (e.g., Bhandari et al., 2020; Mishra et al., 2019; Rafeekh & Mishra, 2021). The L2 composite score was calculated by taking the sum of the z-scores of semantic fluency in L2, the vocabulary test for L2 (WordOrNot) and the self-report of participants in LSBQ about their speaking, listening, reading and writing proficiency in L2, and then dividing it by the square root of the sum of variances and covariances of these three variables with one another. While BCS reflects the degree of bilingualism depending on usage and exposure, the L2 composite score reflects the degree of second language proficiency. We were interested in comparing these scores and examining how they correlate with parallel activation.

## 3. Results

### *3.1. Data Analyses*

Eye movement data were extracted using Data viewer (SR Research, Kanata, ON, Canada) and analyzed in R using the VWPre package (Porretta et al., 2018). Eye movements were analyzed by considering fixations from 200 ms to 1000 ms after word onset. The upper limit was chosen as parallel language activation is typically considered an early effect and diminishes within 1000 ms of spoken word onset. This was also confirmed through visual inspection. It is also widely acknowledged that the minimum time required to program and launch a saccade is 200 ms (Saslow, 1967). Most visual world studies, thus, consider eye movements that begin 200 ms after word onset to reflect the linguistic processing. The screen was divided into four equal quadrants as interest areas. The proportion of fixations to each type of object (TE cohort and Distractor 1, Distractor 2 and Distractor 3) was calculated by dividing the number of fixations to each object by the total number of fixations to the display in that time bin. The fixation proportion to the three distractors was then averaged.

We analyzed overall proportion fixations in the 800 ms window after spoken word onset. Many visual world studies analyze the time course of fixations to examine how language-mediated eye movements evolve. We plotted the time course data for demonstration to visually compare them with the findings of Mishra and Singh (2014). However, we statistically analyzed only the overall proportion of fixations as we did not have specific hypotheses for the different time windows. The proportion data were logit transformed and mixed effects logistic regression was performed using the lme4 package in R (Bates et al., 2014). Glmer function was used with the family specified as binomial and link logit. The spoken word language (L2: +1, L1: −1) and object type (TE cohort: +1, Distractors: −1) were sum-coded as fixed effects and entered into the model. The interaction between the spoken word language and object type was also entered into the model. "Participant" and "Item" were entered as random effects. More complex models with random slopes failed to converge. Statistical significance was determined based on *p*-values generated through the lmerTest package (Kuznetsova et al., 2017). The full model outputs can be found in the Appendices A and B.

Dwell time was analyzed by calculating the total fixation duration at each interest area on each trial. The dwell time on distractors was calculated by averaging the dwell time across the three distractor quadrants. The Lmer function was used to analyze dwell time with spoken word language and object type as factors. To examine the role of proficiency on parallel language activation, we performed correlations between LSBQ BCS, L2 composite score, English proficiency score from the LSBQ and the degree of parallel language activation (proportion of fixations to the TE cohort–proportion of fixations to averaged distractors), for each spoken word language condition. Similar analyses were performed for dwell times.

For the visibility test, responses to each word were analyzed separately. The accuracy for each word was calculated. d′ measures were calculated for each word by calculating the hit rate and false alarm rate. The hit rate was calculated by dividing the number of trials on which the participants clicked left (SAME) and the same word was presented at that location. The false alarm rate was calculated by dividing the number of trials on which participants clicked right (DIFFERENT) but the same word was present at that location. The d′s for all four words were then averaged to yield a single d′ value. t-tests were conducted on accuracy and d′ values to examine if they significantly deviated from chance (50% for accuracy data and 0 for d′).

### 3.2. Proportion of Fixations

There was a main effect of object type, with $t = 7.74$ and $p < 0.001$, indicating that TE cohorts received more looks than distractors. There was no effect of spoken word language, with $t = 0.18$ and $p = 0.855$. The two-way interaction between spoken word language and object type was significant, with $t = 2.78$ and $p = 0.005$, revealing greater parallel activation with English spoken words compared to Hindi spoken words (Figure 2).

Correlational analyses between the degree of parallel language activation (proportion of fixations to TE cohorts–proportion of fixations to distractors) and BCS revealed non-significant correlations for both English spoken words, with $r = -0.19$ and $p = 0.159$, and the Hindi spoken word condition, with $r = 0.19$ and $p = 0.157$ (Tables 1 and 2).

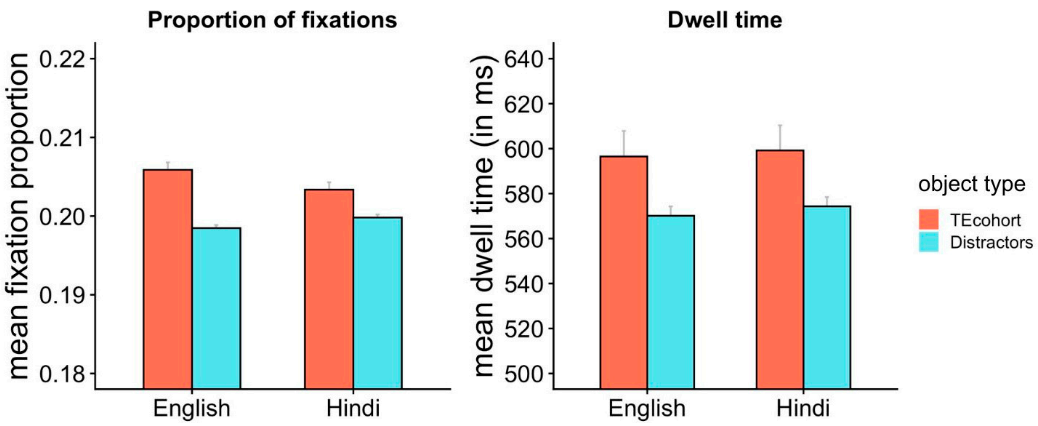


**Figure 2.** Plot showing the proportion of fixations and dwell time for each condition. The spoken word language is plotted along the x-axis. Error bars indicate +1 SE.

**Table 1.** Correlation between degree of parallel language activation and measures of bilingualism for English spoken word condition.

| | Fix Prop Diff | Dwell Time Diff | BCS | English Proficiency | L2 Composite Score |
|---|---|---|---|---|---|
| Fix prop diff | - | | | | |
| Dwell time diff | 0.65 *** | - | | | |
| BCS | −0.19 | 0.15 | - | | |
| English Proficiency | −0.04 | −0.08 | −0.31 * | - | |
| L2 composite score | 0.01 | 0.12 | 0.38 ** | 0.85 *** | - |

Note: Fix prop diff and dwell time diff refer to the difference in means to TE cohort and distractors. "BCS" stands for bilingualism composite score. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

**Table 2.** Correlation between degree of parallel language activation and measures of bilingualism for Hindi spoken word condition.

| | Fix Prop Diff | Dwell Time Diff | BCS | English Proficiency | L2 Composite Score |
|---|---|---|---|---|---|
| Fix prop diff | - | | | | |
| Dwell time diff | 0.56 *** | - | | | |
| BCS | 0.19 | 0.04 | - | | |
| English Proficiency | −0.05 | 0.15 | −0.31 * | - | |
| L2 composite score | −0.17 | 0.13 | 0.38 ** | 0.85 *** | - |

Note: Fix prop diff and dwell time diff refer to the difference in means to TE cohort and distractors. "BCS" stands for bilingualism composite score. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

### *3.3. Dwell Time*

There was a main effect of object type on dwell time, with $t = 3.06$ and $p = 0.002$, indicating that total dwell time was longer for TE cohorts compared to distractors (Figure 2). There was no significant main effect of spoken word language, with $t = 0.38$ and $p = 0.707$. No significant interaction between spoken word language and object type was found, with $t = 0.09$ and $p = 0.928$.

The difference in dwell time between TE cohorts and distractors was not significantly correlated with the BCS scores of the participants for English spoken words ($r = -0.15$, $p = 0.272$) and Hindi spoken words ($r = 0.04$, $p = 0.76$) (Tables 1 and 2).

### *3.4. Accuracy*

In 20% of the trials (30 trials), participants were asked a question, "Was X present?", where X was either one of the four words presented on that trial or a new word. The mean accuracy of responses to this question was 49% and did not significantly differ from chance (50%), with $t$ (1, 57) = 0.92 and $p$ = 0.362.

### *3.5. Visibility*

Accuracy for the four words was 57%, 56%, 53% and 55%. All the four values significantly differed from chance (50%), with $p < 0.001$. Results showed that the average d′ of the four words (mean = 0.4) significantly differed from 0, with $t$ (1, 57) = 10.62 and $p < 0.001$, suggesting that the participants might have had some awareness of the words.

## 4. Discussion

In a visual world study on Hindi–English bilinguals living in India, we presented an auditory spoken word in English or Hindi along with masked printed words on the visual display. One of the printed words was the phonological cohort of the translation equivalent of the spoken word. Analyses of eye movements showed a greater proportion of fixations and higher dwell time on the TE cohorts compared to the unrelated distractors. We take this as evidence that language-mediated eye movements triggered by cross-linguistic activation can proceed even in the absence of full conscious awareness.

These findings nicely replicate the findings of Mishra and Singh (2014), who administered a similar paradigm with unmasked words to a group of Hindi–English bilinguals living in Allahabad. In both studies, we see robust parallel activation as seen through eye movements (Figure 3). Although we did not statistically compare the findings from the two studies, it is apparent from a visual inspection that the magnitude of parallel activation was reduced in the current study compared to Mishra and Singh (2014). This is to be expected as the printed words on the display in the current study were masked. Further, we measured eye movements on a blank screen after the printed words had disappeared. So, it is not surprising that the effects were weaker.

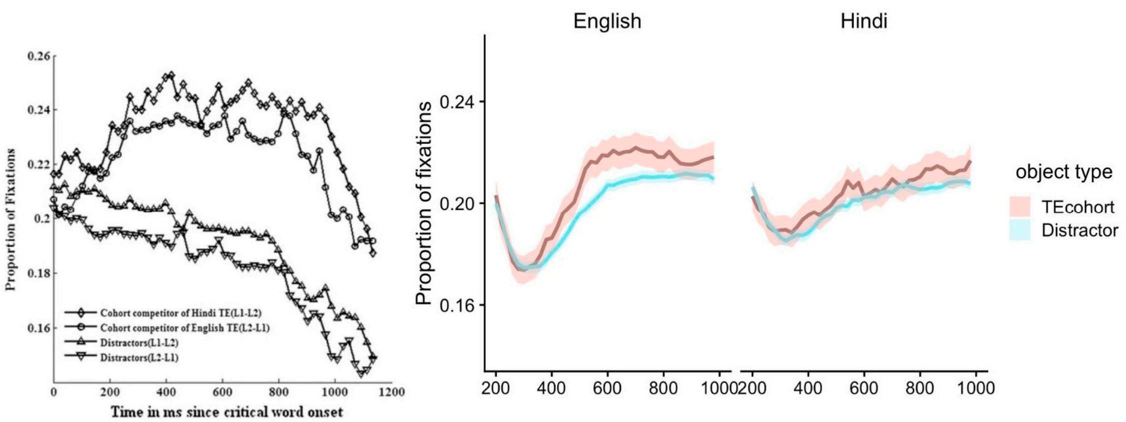


**Figure 3.** Time course plots of cross-linguistic activation from (**left**) Mishra and Singh (2014) and the (**right**) current study for comparison. Both studies used similar paradigms on similar samples except the printed words in the current study were masked.

Greater parallel activation was observed for English (L2) spoken words compared to Hindi spoken words. This does not match the finding of Mishra and Singh (2014), who observed equivalent activation in both language directions. The reason for this discrepancy is not clear. Studies on translation activation in bilinguals sometimes find an effect of language direction depending on the language pairs, the proficiency level of the participants and the language context. For instance, the Revised Hierarchical Model (RHM, Kroll & Stewart, 1994) predicts that late learners of L2 rely more on the translation route between L2 and L1 for comprehension in L2. Translation is not necessary for L1 comprehension. This often results in greater activation of L1 when listening to L2 words. However, this prediction is valid for late learners of L2, whereas participants in our study were fairly highly proficient in L2. It is possible that when the words are masked, even highly proficient users of L2 rely on the translation route for L2 comprehension. This points towards an important role of conscious awareness in bilingual language processing models, and further studies are necessary to investigate this issue.

Proficiency did not seem to play a role in the degree of parallel activation. There were no significant correlations between the degree of bilingualism (BCS score) or L2 proficiency (English proficiency and L2 composite scores) and the degree of parallel activation. This was surprising and contradictory to earlier studies published on Hindi–English bilinguals in India. Although Mishra and Singh (2014) did not assess the role of proficiency in their study, a few other studies by Mishra and colleagues have shown that second language proficiency modulates parallel activation in bilinguals (e.g., Mishra & Singh, 2016). It is possible that the effects were weak because of the masked words and not large enough to show subtle modulations due to differences in proficiency.

Unconscious processing is often equated with automaticity. Thus, it could be tempting to conclude that language-mediated eye movements of the kind observed in this study are a result of automatic processes since we have shown that they occur in the absence of complete awareness. We have previously shown that cross-linguistic activation as seen through eye movements in a visual world paradigm is susceptible to resource limitations (Prasad et al., 2020; Prasad & Mishra, 2021). In particular, Prasad and Mishra (2021) showed that a concurrent working memory load constrains parallel activation. This study is worth mentioning for several reasons: the same task and stimuli from Mishra and Singh (2014) were used and thus closely resemble the design of this study. Also, the sample in both studies was taken from the same population—Hindi–English bilinguals at the same university. Thus, it appears that the unconscious nature of language-mediated eye movements does not necessarily mean that they are a result of automatic processing.

We found that the performance on the visibility task was significantly above the chance level. This may be an artefact of the way we administered the task rather than a true indicator of the visibility of the words. We asked for the same or different judgments here, which makes the task slightly easier for the participants, so even if they had gotten a glimpse of a letter, they might have given the correct response. Instead, if we had asked people to type in the masked words, then it is possible that the performance would have been much worse. Some studies have reported above-chance accuracy on a visibility test while they subjectively reported having "seen" nothing (Koivisto & Neuvonen, 2020). This could be possible due to a blindsight-like phenomenon in which the masked stimuli trigger responses without participants being consciously aware of them. When we took subjective feedback from the participants at the end of the experiment, most of them reported that they could not see the words at all, suggesting that the masked words were indeed unconscious. It is also important to note that the visibility test was conducted in a separate session with all the stimuli used in the main experiment. Thus, the participants were viewing the stimuli for the second task. The analyses of the responses to the yes/no judgement task in the main experiment were at chance level, suggesting that participants might not have had full awareness of the words. There is an ongoing debate on the best method to assess the lack of conscious awareness (Sandberg et al., 2010).

We used a same/different judgement task, which forced participants to make a binary choice based on their awareness of the word. Some researchers have argued that conscious awareness is not an all-or-none phenomenon and it is more useful to assess the degree of awareness (Overgaard et al., 2006). In line with this, researchers are increasingly using subjective measures of unconscious perception (Francken et al., 2022), such as the perceptual awareness scale (Ramsøy & Overgaard, 2004). It would be useful to include such subjective scales in the future to obtain a more fine-grained measure of conscious awareness.

In conclusion, our study shows that parallel language activation can proceed in the absence of full conscious awareness. We showed this by measuring eye movements in the visual world paradigm. Converging evidence can also be sought using other paradigms such as the lexical decision or the translation priming task. Future studies also need to replicate the key finding with alternate measures of both inducing and measuring lack of awareness. More research is also needed to further elucidate the role of language direction between different language pairs. An important future direction of this research is to examine the role of context. Several studies have shown that the cultural and interlocutor context of a bilingual significantly changes their language processing (Berkes et al., 2018; Kapiley & Mishra, 2019; Woumans et al., 2015; Zhang et al., 2013). It would be important to investigate whether unconscious parallel language activation is also susceptible to contextual effects. Such a finding would be an important contribution to the literature on the interactivity of the bilingual mind.

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## Appendix A. Proportion of Fixations

logit_lme <- lmerTest::lmer(Looks ~ languagesumcoded X IAsumcoded + (1 | Subject) + (1 | Item), data = logit_filtered).

| | Estimate | Std. Error | df | t Value | Pr(>\|t\|) |
|---|---|---|---|---|---|
| (Intercept) | $-2.211 \times 10^{0}$ | $3.715 \times 10^{-2}$ | $6.907 \times 10^{-1}$ | −59.504 | $<2 \times 10^{-16}$ *** |
| languagesumcoded | $2.133 \times 10^{-3}$ | $1.167 \times 10^{-2}$ | $1.480 \times 10^{2}$ | 0.183 | 0.8553 |
| IAsumcoded | $2.043 \times 10^{-2}$ | $2.639 \times 10^{-3}$ | $6.958 \times 10^{5}$ | 7.740 | $9.98 \times 10^{-15}$ *** |
| languagesumcoded:IAsumcoded | $7.343 \times 10^{-3}$ | $2.639 \times 10^{-3}$ | $6.958 \times 10^{5}$ | 2.782 | 0.0054 ** |

** $p < 0.05$; *** $p < 0.001$

## Appendix B. Dwell Time

DwellTime_lme <- lmerTest::lmer(DwellTime ~ IAsumcoded X languagesumcoded + (1 | Subject) + (1 | Item), data = Dwell_time_filtered).

| | Estimate | Std. Error | df | t Value | Pr(>\|t\|) |
|---|---|---|---|---|---|
| (Intercept) | 585.0248 | 11.9991 | 58.8995 | 48.756 | $<2 \times 10^{-16}$ *** |
| languagesumcoded | 12.8085 | 4.1833 | 17,180.9524 | 3.062 | 0.0022 ** |
| IAsumcoded | −1.7007 | 4.5179 | 147.9703 | −0.376 | 0.7071 |
| languagesumcoded:IAsumcoded | 0.3772 | 4.1833 | 17,180.9524 | 0.090 | 0.9282 |

** $p < 0.05$; *** $p < 0.001$

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