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Using virtual reality to study reading: An eye-tracking investigation of transposed-word effects

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A B S T R A C T

Eye movements were recorded using a virtual reality (VR) set-up as participants made grammatical decisions to sequences of words. Ungrammatical decisions were harder to make to transposed-word sequences (*The white was cat big*) compared with control sequences where transposing two adjacent words never produces a correct sentence (*The black ran dog fat*). Crucially, we found significant transposed-word effects independently of the order in which the two critical words were fixated (i.e., *was* before *cat* vs. *cat* before *was*), thus falsifying a reading out-of-order account of transposed-word effects.

1. Introduction

1.1. Theoretical background

Eye-tracking has a long history in psycholinguistic research ever since the invention of the first eye-tracker (Huey, 1908). It has been a paradigm of choice for investigating on-going lexical, syntactic, and semantic processing during natural reading. Such investigations have shown that certain eye movement measures, such as the time spent looking at a word, likely reflect on-line processing difficulty (see Rayner, 1998, 2007, for reviews). These investigations were led by a relatively small group of researchers who, at the time, had access to the equipment that could provide spatially and temporally accurate eye movement recordings. However, recent technological advances have opened up different means to achieve such recordings, and, depending on the level of precision that is required given the hypotheses under test, these advances should help democratize eye movement research. Virtual Reality (VR) goggles offer one such possibility, that moreover provide the advantage of providing complete control over the entire field of vision during an experiment and allowing free head movements.

In the present study we show how VR goggles can be used to record eye movements during reading in an experiment where the main goal is to monitor the order in which the different words are read. This study is motivated by a recent finding (Mirault et al., 2018; Snell and Grainger, 2019a), and as a test of one specific explanation of this finding. Mirault et al. (2018) asked participants to judge as rapidly and as accurately as possible whether a sequence of words presented under free viewing conditions formed a grammatically correct sentence or not. The focus of that study was on two types of ungrammatical sequence: one formed by transposing two adjacent words in a grammatically correct sequence (e.g., *The white was cat big*) and a matched control sequence that could not be resolved into a correct sentence by transposing any two words (e.g., *The black ran dog fat*, Mirault et al. (2018) found that the transposed-word sequences were harder to reject than the control sequences – a transposed-word effect in grammaticality judgments. They interpreted this finding as reflecting parallel processing of word identities and the noisy association of these word identities to spatiotopic locations along a line of text (see Snell and Grainger, 2019b, for a summary of the evidence in favor of parallel processing models of reading). These findings fit with the strong parallel processing approach advocated by Kennedy and Pynte (2008) on the basis of their observation of a large number of out-of-order fixations during reading that had little impact on processing difficulty.

However, one earlier study had investigated transposed-word effects in an arguably more natural reading situation, and came to diametrically opposite conclusions (Rayner et al., 2013). Using the boundary technique (Rayner, 1975), Rayner et al. (2013) compared preview effects of two-word previews that could either be a transposition of the normal continuation of the sentence, two unrelated words, or an identical preview. Thus, for example, in the transposed-word preview condition the regular sentence “The neighbor painted the white walls black” would be first presented as “The neighbor painted the walls white black” up to the point where readers’ eyes crossed the invisible boundary between “the” and “walls”, at which point the regular continuation was restored. Rayner et al. (2013) found increased processing difficulty with transposed-word

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previews compared with identical previews. The authors concluded in favor of a serial processing account of reading, as exemplified in the EZ Reader model (Reichle et al., 1998), and against the extreme parallel processing view proposed by Kennedy and Pynte (2008), later developed by Snell et al. (2017) and implemented in the OB1-reader model (Snell et al., 2018). Rayner et al. suggested that their experimental manipulation provided a more direct test of canonical word order processing than the corpus analysis of Kennedy and Pynte. On the other hand, we would argue that the combination of a word transposition and a parafoveal preview manipulation in the Rayner et al. study left open the possibility that much of the interference observed in the transposed-word condition was driven by prelexical incompatibilities between the transposed words and their regular replacements. We would therefore further argue that a transposed-word manipulation combined with normal reading and grammaticality judgments (Mirault et al., 2018) is a better test of parallel processing accounts of transposed-word effects.

Serial models can nevertheless account for the transposed-word effects reported by Mirault et al. (2018) by assuming that the two words were in fact read out of order on some occasions. That is, participants would actually be skipping the first word so as to fixate the word on the right before regressing back to the word on the left, and therefore be reading the transposed words in their grammatically correct order. Paradoxically, it is precisely the work of Kennedy and Pynte (2008) that suggests that this is indeed possible. Therefore, to put this explanation to test, in the present study we tested the materials used in the Mirault et al. study while monitoring participants' eye movements. Finally, the use of a central fixation cross in the Mirault et al. (2018) study has been criticized as potentially inducing an unnatural reading strategy. Hence a sequence-initial fixation was used in the present study.

1.2. Methodological background

1.2.1. Eye-tracking techniques

Currently, there are three mains kinds of techniques used to record the “point of regard” (POR; Young and Sheena, 1975): i) electro-oculography (EOG), that measures voltage differences across electrodes placed on the skin around the eyeball; ii) the scleral contact lens coil (one of the most precise eye tracking systems) that uses a mechanical reference object mounted on a contact lens which is placed on the eye; and iii) video-oculography (VOG) that measures the features of the eyes under rotation and translation such as pupil shape, position of the limbus (the iris-sclera boundary), and corneal reflections (typically using an infra-red light beam). VOG devices have become wide-spread and the most recent algorithms are currently implemented on webcams, smartphones, and Head-Mounted Displays (HMD).

1.2.2. Why use virtual reality?

Virtual Reality (VR) helmets allow users to see an artificial world on 360° and to integrate themselves in an immersive way. Among the many benefits of such systems, there is the fact that all external visual noise that can appear in ‘classic’ experimental settings can be removed. The VR helmet totally encompasses the visual field and therefore participants cannot be distracted or influenced by visual stimuli other than those involved in the experiment at hand. These systems have found useful medical applications such as in the treatment of phobias and other anxiety disorders (see Krijin, Emmelkamp, Olafsson and Biemond, 2004, for a review). A number of studies have used eye-tracking in a VR environment (Skulmowski et al., 2014; Duchowski et al., 2000; Tanriverdi and Jacob, 2000; Iwamoto et al., 1994; Pfeiffer et al., 2008; Triesch et al., 2002) but none of them have used a reading task (see Peeters, 2019, for a review). The present study is therefore, to our knowledge, the first to use eye-tracking in a VR environment to study reading. In the Discussion, we further examine the potential pros and cons of using a VR set-up compared with traditional high-resolution laboratory eye-trackers to study reading.

2. Methods

2.1. Participants

Analysis of the power of our previous study (Mirault et al., 2018, laboratory experiment) revealed a Cohen's d equal to 0.62 (greater than medium power, Cohen, 1988) for the effect in error rates, where the transposed-word effect was strongest. We therefore opted to use the same number of participants (for an equivalent number of stimuli) as in that study. Forty participants (29 female) were recruited at Aix-Marseille University (Marseille, France). They were all native French speakers and received either course credit or monetary compensation (€10/hour). All the participants reported normal or correct-to-normal vision and ranged in age from 18 to 29 years (M = 22.02, SD = 2.22). They were naïve to the purpose of the experiment and signed an informed consent form before starting the experiment. Ethics approval was obtained from the Comité de Protection des Personnes SUD-EST IV (No. 17/051).[1]

2.2. Design & stimuli

The design and stimuli were identical to the Mirault et al. (2018) study. We focus here on the two types of ungrammatical sequence tested in that study: the transposed-word sequences and their matched control sequences. These provide the two levels of the Transposition factor.

2.3. Apparatus

The VR environment was created using Unity software (Unity Technologies ApS) and was displayed on a WQHD OLED screen (2560 x 1440 pixels) covering up to 100 degrees of visual angle with a refresh rate of 70 Hz. Eye movements were recorded using the infra-red eye-tracker in the virtual reality headset Fove 0 HMD (FOVE, Inc.). Recording was binocular with a high spatial accuracy (<1°) and a sampling rate of 120 Hz (because the C# routines we used were developed with Microsoft Visual Studio Cohen, 1988 for Unity, the sampling rate of the tracker matched the sampling rate of the screen (i.e., 70 Hz). The position of the head was obtained combining a USB Infra-Red position tracking camera with a refresh rate of 100 Hz and an Inertial Measurement Unit (IMU) placed in the headset. A recent graphic card (NVIDIA GeForce GTX 1080 Ti) was mounted on a computer (Dell Precision 5820) to display the VR environment in the Fove headset. The VR environment was also duplicated on an LCD screen (Asus PG258) running with a high refresh rate (240 Hz) for the experimenter.

From the eye tracker, we recovered 6 measures per eye: three for the origins (x, y, and z) and three for the Gaze Intersection Point (GIP). We defined the Origins as the viewer-local coordinates mapped from eye tracker screen coordinates to the near view plane coordinates. The GIP is given by the addition of a scaled offset to the view vector originally defined by the helmet position and central view line in virtual world coordinates (from *Eye Tracking methodology*; Duchowski, 2007). One particularity is that the Fove 0 settings were created assuming that the two GIPs did not necessarily converge onto the same location.

2.4. Procedure

Participants were seated in a dark and quiet room and free to move the head and the torso. At the beginning of the experiment, the participant's eye position was calibrated using a 5-point calibration grid. Dots appeared on the VR screen with a decreasing size. Participants were instructed to focus on the center of the dots. Then, the instructions (that had already been explained by the experimenter) were presented on the screen and the participant had to push a button on an ergonomic

[1] All scripts are available on OSF at the following link: https://osf.io/smbv7/?view_only=3595ce9b9086401c8f17d242d3953a97.

gamepad to start the experiment. They had the possibility to remove the headset at any time of the experiment. Each trial started with a fixation cross located 191.27 pixels left of the beginning of the first word of the sequence (Min = 41.35 pixels, Max = 348.55 pixels, SD = 51.92) and when the experimenter (experienced with eye tracking studies) judged that the participant's fixation was stable, (s)he triggered the display of the stimulus. The word sequences were presented in the middle of the virtual reality visual field. The sequence remained at this location independently of head and eye movements. Therefore, the location of the word sequence remained the same throughout the experiment and was not gaze or head contingent. Fig. 1 provides a very approximate illustration of the viewing conditions of an example sentence. Participants were instructed to read the word sequence from left to right and press the right button on the gamepad if the sequence was grammatically correct or the left button if the sequence was not grammatically correct, as fast and as accurately as possible (i.e., a grammatical decision task, Mirault and Grainger, 2020).

2.5. Pre-processing of eye movement behavior

We used the *emov* package (created by Simon Schwab in 2016) in the R statistical computing environment (R Core Team, 2018). This package implements a dispersion-based algorithm (I-DT) proposed by Salvucci and Goldberg (2000) which measures fixation durations and positions. Prior to analysis we excluded fixations that lasted less than 100 ms.

2.6. Analyses of eye movements

We used Linear Mixed-Effects models (LMEs) to analyze our data, with items and participants as crossed random effects, including by-item and by-participant random intercepts (Baayen et al., 2008). Items in these analyses were the sentences. Generalized (logistic) LMEs were used to analyze error rates. The models were fitted with the *lmer* (for LMEs) and *glmer* (for GLMEs) functions from the lme4 package (Bates et al., 2015) in R. We report regression coefficients (b), standard errors (SE) and |t-values| (for LMEs) or |z-values| (for GLMEs) for all factors. Fixed effects were deemed reliable if $|t|$ or $|z| > 1.96$ (Baayen et al., 2008). All durations were inverse-transformed (−1000/duration) prior to analysis.

3. Results

We recorded both gamepad responses and eye-tracking measures. Concerning the behavioral response measures, we recorded error rates and the response times (RTs) in the grammatical decision task. Concerning the eye-tracking measures, we computed fixation durations and fixation probabilities (within-word re-fixations and skipping rate). All participants performed with accuracy greater than 85%. None were excluded prior to analysis. Participants were debriefed after the experiment and asked if they had experienced any discomfort such as nausea or dizziness, even mildly so. No participant reported any discomfort whatsoever.

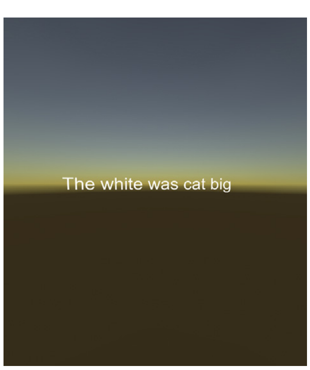

Fig. 1. Illustration of a sequence of words in the virtual reality environment. It is important to note that the word sequence remained in the same position in the virtual reality set-up independently of eye and head movements, as it would in a real-life setting.

3.1. Global measures

Here we analyzed errors and response times (RTs) in the grammatical decision task, as well as the total viewing times (the sum of fixation durations across all words per trial, including regressions) in the eye-tracking data.

3.1.1. Error rates

There was a significant effect of Transposition ($b = 0.85$, SE = 0.25, z = **3.34**) with more errors in the transposed-word condition (M = 16.12%, IC 95% = 0.11) compared to the control condition (M = 5.56%, IC 95% = 0.07).

3.1.2. Response times

We observed longer RTs in the transposed-word condition (M = 1694 ms, IC 95% = 139.72) compared to the control condition (M = 1653 ms, IC 95% = 131.82), but this effect failed to reach significance ($b = 0.00$, SE = 0.00, t = 1.52).

3.1.3. Total viewing times

There was a significant effect of Transposition ($b = 0.03$, SE = 0.01, t = **2.48**), with longer viewing times in the transposed-word condition (M = 1263 ms, IC 95% = 135.11) compared to the control condition (M = 1232 ms, IC 95% = 131.34).

3.2. Local measures

Here we analyzed eye movement behavior (fixation probabilities, fixation durations) on the two critical words that were involved in the transposition and the corresponding words in the control condition. We first analyzed the combined probabilities and durations for the two words before analyzing each word separately.

3.2.1. Fixation probabilities

The effect of Transposition on skipping rates was not significant ($b = 0.04$, SE = 0.15, z = 0.28), with an identical skipping rate in the transposed-word condition (M = 0.17, IC 95% = 0.11) and the control condition (M = 0.17, IC 95% = 0.11). Although refixation probabilities were higher in the transposed-word condition (M = 0.31, IC 95% = 0.14) than the control condition (M = 0.28, IC 95% = 0.14), this effect was not significant ($b = 0.17$, SE = 0.11, z = 1.52). The separate analyses of each critical word revealed the same pattern of non-significant effects for the Transposition factor in skipping rate (word1: b = 0.08, SE = 0.08, z = 1.07; word2: b = 0.02, SE = 0.08, z = 0.28) and for refixation probabilities (word1: b = 0.19, SE = 0.16, z = 1.20; word2: b = 0.02, SE = 0.22 z = 0.09).

3.2.2. Fixation durations

The total viewing time of the two critical words was greater in the transposed-word condition (M = 283 ms, IC 95% = 41.02) than the control condition (M = 274 ms, IC 95% = 40.09), but this difference failed to reach statistical significance ($b = 0.09$, SE = 0.06, t = 1.32). The separate analyses of each critical word revealed the same pattern of non-significant effects for the Transposition factor on total viewing time (word1: b = 0.01, SE = 0.08, t = 0.16; word2: b = 0.12, SE = 0.10, t = 1.61).

3.3. Order of fixations and grammatical decisions

We first calculated the proportion of trials on which the critical words were read out-of-order (word2 then word1) and tested whether this

Table 1
Average error rates in the grammatical decision task and summary statistics (GLMEs) for the transposition effect (transposed-word vs. control) as a function of the order in which the two critical words were read. Bold values represent the significant values (i.e., superior to 1.96).

	Means (IC 95%)		GLMEs		
	Transposed-word	Control	*b*	SE	*z*
In-order	14.09 (0.10)	5.29 (0.06)	1.28	0.27	**4.70**
Out-of-order	17.32 (0.11)	6.45 (0.07)	1.41	0.31	**4.53**

Bold values represent the significant values (i.e., superior to 1.96).

differed across the transposed-word and control conditions. The probability was actually lower in the transposed-word condition (M = 0.34, IC 95% = 0.26) compared with the control condition (M = 0.35, IC 95% = 0.24), but this difference was not significant (*b* = 0.03, SE = 0.12, z = 0.28). In a final, but crucial analysis, we examined whether the order of fixation of the two critical words (in-order: word1 then word2 vs. out-of-order: word2 then word1) impacted on the transposition effect in grammatical decision errors. The results of this analysis are shown in Table 1. Significant transposition effects were found in both conditions.

4. Discussion

The present study used eye-tracking with virtual reality (VR) goggles in order to i) demonstrate the feasibility of using such equipment to study reading, and ii) test one specific interpretation of transposed-word effects reported in a previous sentence reading study without eye-movement recordings. In that previous study (Mirault et al., 2018), participants read sequences of words that either formed a correct sentence or were ungrammatical sequences and had to decide as rapidly and as accurately as possible if the sequence was grammatically correct or not. Mirault et al. examined RTs and error rates for two types of ungrammatical sequence: one that was created by transposing two adjacent words in a correct sentence (e.g., *The white was cat big*), and one that could not be resolved into a correct sentence by transposing any two words (e.g., *The black ran dog fat*). Participants in that study found it harder to classify the transposed-word sequences as being ungrammatical compared with the matched control sequences.

The present study used the same stimuli and task as in the Mirault et al. (2018), with two important modifications. First, we recorded participants' eye movements as they read the word sequences in order to make a grammatical decision. Second, the initial fixation cross was in the center of the screen in the Mirault et al. study, whereas here it was located just to the left of the first word in the sequence. These two changes were operated in order to address criticism from the serial reading community that i) a central fixation would produce unnatural reading behavior, and ii) that the transposed-word effect could be driven by participants sometimes reading the transposed-words out-of-order, that is, in their grammatically correct order.

We found significant transposition effects in errors in the grammatical decision task and in the total viewing times for all words in the sequence, thus demonstrating that these effects can be obtained when the initial fixation mark is at the beginning of the sequence. Most important is that we found significant transposition effects in grammatical decision errors when only analyzing trials where participants looked at the transposed-words in the order in which they were presented in the sequence (the "in-order" condition of Table 1). Overall, participants looked at the transposed-words in the order in which they were presented on more than 60% of trials, but what is clear from our analysis is that the remaining trials, where the transposed-word were read in their grammatically correct out-of-order, were not driving the overall transposition effects we observed. In line with this analysis is that fact that eye fixation probabilities did not differ between the transposed-word and the control conditions, thus demonstrating that the presence of transposed-words did not encourage participants to skip the critical words or refixate these words more so than when no such transposition was present. These results therefore allow us to reject one account of transposition effects offered by a strictly serial model of reading (e.g., Reichle et al., 1998).

Finally, the present study aimed to demonstrate that a VR headset equipped with an in-built eye-movement recording system provides a cost-effective means of recording eye-movements during text reading. The immersive nature of the display and the absence of external visual perturbations provide one potential asset for studying behavioral responses, including eye movements, to all kinds of visual stimuli. Another advantage is the relatively low cost of VR equipment, although we acknowledge that this financial advantage might diminish as less expensive desk-top or head-mounted eye-trackers become available. The obvious drawbacks, on the other hand, are the less natural reading environment compared with everyday reading behavior, and the lower spatial resolution of the VR eye-tracker used in the present study. A further drawback with the present set-up was that the experimenter had to initiate every trial after deciding that the participant had fixated on the fixation cross. This procedure has been automatized in our more recent experimental scripts which we have also made available on OSF. Finally, we note here two examples of applications for VR eye-trackers in reading research where the VR environment might provide further advantages: i) to investigate reading in understudied situations, such as reading information on billboards or information panels while driving; and ii) the practical advantage of using such equipment to study reading in young children and in particular the user-friendly, game-like nature of the set-up that children appear to appreciate (we have recently successfully completed a VR reading study with 102 children between 7 and 9 years old). In conclusion, we would therefore argue that VR eye-trackers offer an interesting complementary method for the investigation of reading behavior.

Declaration of competing interest

The authors declare that there are no conflicts of interest.

CRediT authorship contribution statement

Jonathan Mirault: Conceptualization, Methodology, Software, Writing - original draft, Writing - review & editing, Formal analysis. **Agnès Guerre-Genton:** Conceptualization, Software. **Stéphane Dufau:** Conceptualization, Methodology, Software. **Jonathan Grainger:** Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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