Readers with less cognitive control are more affected by surprising content: Evidence from a self-paced reading experiment in German

Bruno NICENBOIM[†], Shravan VASISHTH[†], and Reinhold KLIEGL[‡]

[†] Departament of Linguistics, University of Potsdam
Haus 14, Karl-Liebknecht-Str. 24-25, D-14476 Potsdam, Germany
[‡] Department of Psychology, University of Potsdam
Haus 14, Karl-Liebknecht-Str. 24-25, D-14476 Potsdam, Germany

E-mail: bruno.nicenboim@uni-potsdam.de

Abstract A mechanism of predictions for language implies that the parser has to build up potential upcoming continuations and then evaluate them given the evidence. We show that the difficulty produced by the mismatch between the actual continuation and the predictions is modulated by cognitive control as measured by a modification of the Stroop task. We ran a self-paced reading task in German using a paradigm similar to the one from DeLong et al. (2005) and Van Berkum et al (2005). Our results show a larger slowdown for readers with less cognitive control while reading surprising content. The results suggest that cognitive control modulates the ability to suppress irrelevant predictions.

Key words predictions, surprise, cognitive control, individual differences, German

1 Introduction

It has been consistently shown that context-predictable words are read more quickly and skipped more often than less predictable words. However, context-induced benefits that are assessed via the predictable word itself can also emerge once this word has been read, because of an easier integration into the wider context.

A series of studies has shown an effect of gender, phonology, or animacy expectancy at the determiner or adjective prior to the target predicted noun (DeLong, Urbach, & Kutas, 2005; Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005; Van Berkum et al., 2005; Otten, Nieuwland, & Van Berkum, 2007; Otten & Van Berkum, 2008; Otten & Van Berkum, 2009; Wicha, E. A. Bates, Moreno, & Kutas, 2003; Wicha, Moreno, & Kutas, 2003; Wicha, Moreno, & Kutas, 2004; Szewczyk & Schriefers, 2013). The basic idea of all these experiments is that a strong prediction for a noun phrase will trigger expectations of certain features in its previous determiner or adjective. DeLong et al.'s (2005) study, for example, took advantage of a phonological feature of the English language in which different indefinite articles, *a* and *an*, are used depending on the initial phoneme of the immediately following word. In sentences like (1), the predicted article *a* elicited a smaller N400 effect than the unexpected *an* in their ERP study.

(1) DeLong et al. (2005)
   a. The day was breezy so the boy went outside to fly **a** kite.
   b. The day was breezy so the boy went outside to fly **an** airplane.

This paper presents an reading time (RT) study that aims to investigate individual differences in the processing of expected and unexpected upcoming words using a similar paradigm as the one presented before. Three candidates for the individual differences that may account for the variance in processing predictions are working memory capacity, reading skills, and cognitive control.

Working memory capacity If the processes involved in the anticipation of upcoming language depend on working memory capacity, the reduced ability to temporarily store and manipulate information of low-capacity readers would lead them to be less able to anticipate upcoming words in text, relative to high-capacity readers. Thus subjects with more working memory capacity should read faster the determiner that matches the feature expected according to the predicted upcoming noun.

However, Otten and Van Berkum (2009) investigated this using EEG and found that low capacity participants showed an additional ERP response that was not present in the high capacity group. They suggest that differences in working memory capacity may not influence the ability to predict upcoming words, but the way in which readers deal with information that disconfirms the generated prediction.

Reading skills Since skilled readers are more sensitive to the semantic cues available to them (Pearlmutter & MacDonald, 1995), they may also be able to predict

the upcoming material better showing a speed-up when they face a determiner with the predicted features.

Cognitive control Cognitive control ability as measured by the Stroop task is related to the suppression of irrelevant information and the maintenance of context-relevant information. Suppression ability has been argued to be crucial to successful and efficient language comprehension, according to Structure-Building Framework (Gernsbacher, 1997). This model suggests that readers with less suppression ability are able to successfully and efficiently enhance relevant information, but are impaired at suppressing irrelevant information during comprehension.

This idea was examined in Boudewyn, Long, and Swaab's (2012) EEG study that investigated the effect of cognitive control (as well as working memory capacity and vocabulary size) in associative priming: the processing benefit for a target word when it is preceded by an associatively related prime word, for example a benefit for *oranges* after reading or hearing *apples*.

The results of Boudewyn et al.'s (2012) study showed stronger N400 effects in words that were unassociated to the prime word (2b) than in associated ones (2a) and verified the predictions regarding cognitive control: participants with less cognitive control, that is participants that performed poorly in the Stroop task, showed stronger N400 effects in words that were unassociated to the prime word (2b) than in associated ones (2a).

(2) (Boudewyn et al., 2012)

a. In her haste she forgot to buy the apples and **oranges**.

b. In her haste she forgot to buy the apples and **bread**.

Associative priming may be a special case of the general mechanism used to make predictions. If that is the case, we would expect that readers with less cognitive control will fail to inhibit the predicted word (and its features) more often when they are reading a determiner with unpredicted features, hence showing longer RTs for the unpredicted determiner.

2 Methods

2.1 Pretest (Sentence completion task)

Thirty-eight German subjects (mean: 23 years old, *SD*: 5 years) completed 53 sentences like (3) at their own pace together with 57 unrelated sentences. (Two participants were excluded: one participant did not take the experiment seriously and the other was not computer literate enough).

(3) Der Bäcker schob den Teig in ...
The baker put the dough in...

The cloze probability of the noun was based on the first noun in the continuation of the sentences; when two nouns had the same stem, their cloze probabilities were summed. In the previous example (3) *Ofen* (oven), *Backofen* (backing oven), and *Steinofen* (stone oven) were nouns given by participants, and their probabilities were added up together giving a total of 0.97.

Twenty-six sentences with nouns with cloze probability over 0.61 where selected. Based on these sentences, 26 experimental items with two conditions such as (4) were built. The "predicted" condition used the noun with the highest cloze probability of the possible continuations (0.97 in ex. 4a), while the noun of the "unpredicted" condition was made up or based on a low cloze probability continuation (lower than 0.25). The unpredicted noun was in all the cases a plausible continuation.

(4) a. Der Bäcker schob den Teig in **seinen**
The baker put the dough in **his.masc**
Ofen und wartete.
oven and waited

b. Der Bäcker schob den Teig in **seine**
The baker put the dough in **his.fem**
Mikrowelle und wartete.
microwave and waited

2.2 Self-paced reading task and assessment of individual differences

Eighty-one German speakers participated in a self-paced reading experiment (Just, Carpenter, & Woolley, 1982). In order to measure reading skills, working memory capacity, and cognitive control ability, participants performed a rapid automatized naming task (Denckla & Rudel, 1976; Nicenboim, Vasishth, Gattei, Sigman, & Kliegl, 2014), an operation span task (Turner & Engle, 1989; Conway et al., 2005; Malsburg & Vasishth, 2012), and a variation of the Stroop task (Stroop, 1935) based on De Houwer's (2003) experiment with a neutral condition as suggested by Brown (2011).

Rapid automatized naming We used a version of rapid automatized naming where participants have to name aloud letters and digits as quickly as they can. Variations in rapid automatized naming time provide a strong predictor of reading skills (Denckla & Rudel, 1976; Nicenboim et al., 2014)

Operation span task The operation span task combines verification of brief mathematical equations with recall letters that follow immediately after each equation. Partial-credit unit scores, which indicate the mean proportion of correctly recalled items (Conway et al., 2005), were used as a numeric score of individual working memory.

Modified Stroop task We used a two-choice button-press version of the Stroop paradigm based on De

Houwer (2003), with two colors associated with each response hand, but we added a neutral condition (Brown, 2011). This manipulation allowed five conditions: congruent (CO; word and color are the same), incongruent at the semantic level (SI; word and color are different, but mapped onto the same response hand), incongruent at both semantic and response levels (RI; word and color are different and mapped onto opposite response hands), and neutral (N: non color word). This modification of De Houwer's (2003) design assumes a "subtractive" logic where: CO < N < SI < RI, and where SI-N is associated with semantic conflict. We used sematic conflict as a measure of cognitive control (De Houwer, 2003).

3 Results

3.1 Data Analysis

The data analysis was conducted in the R programming environment (R Core Team, 2013), using linear mixed-effects models (LMM; Pinheiro and D. M. Bates, 2000) with the package *lme4* (D. M. Bates, Mächler, Bolker, & Walker, 2014). The appropriate transformations of the dependent variable was determined using the Box-Cox method (Box & Cox, 1964; Kliegl, Masson, & Richter, 2010) with the boxcox function in the MASS package (Venables & Ripley, 2002) and was the reciprocal transformation. For large samples, the t distribution approximates the normal distribution and an absolute value of t larger than 2 indicates a significant effect at $\alpha = 0.05$. For all the models presented in the study, covariates were scaled and centered.

3.2 Individual differences

3.2.1 Reading skills (rapid automatized naming)

Average character speed for the rapid automatized naming task for measuring reading skills ranged between 1.79–5.16 characters/second with an average of 2.96 (SE: 0.02) characters/second.

3.2.2 Working memory capacity (operation span task)

Partial-credit unit scores (Conway et al., 2005) for the operation span test measuring working memory capacity of the 81 participants ranged between 0.300–0.983 with an average of 0.664 (SE: 0.017)[1].

3.2.3 Cognitive control (Stroop task)

A linear mixed model using sliding contrasts and including accuracy (wrong coded as 1 and correct as 0), its interaction with the Stroop conditions and with random slopes by subject verified that CO < N < SI < RI held. We found that the contrasts CO-N (Coef = 0.03, $SE = 0.01$, $t = 3.69$), N-SI (Coef = 0.02, $SE = 0.01$, $t = 2.93$), and SI-RI (Coef = 0.05, $SE = 0.01$, $t = 5.90$) were significant, and the differences were in the expected direction.

A single measure of Stroop interference associated with semantic conflict (SI-N) was created. We removed reaction times that were three standard deviations from the mean reaction time of each participant and reaction times associated with wrong answers, and we created a score that was the component associated with difference between the SI condition and the N condition in a principal component analysis (since SI and N conditions were highly correlated).

3.3 Self-paced Reading experiment

Critical region (gender marked determiner) We found a numerical difference between the predicted and unpredicted condition (Coef = 0.01, $SE = 0.01$, $t = .81$) showing that the predicted condition was read faster than the unpredicted. There was a significant effect of reading skills, as well, (Coef = -0.19, $SE = 0.06$, $t = -3.03$): participants with higher reading skills had shorter RTs than participants with lower reading skills. As we expected, there was a significant cognitive control (semantic conflict) × condition interaction (Coef = -0.05, $SE = 0.01$, $t = -3.61$), as cognitive control ability decreased, the RTs at the determiner for the unpredicted condition were larger. This was also true for a length-corrected model by taking the residuals of a mixed-effects model that had 1/RT as the response variable, word length as a fixed effect, and a by-subject and by-items intercept.

Spillover region (noun) Since the region varied in length across conditions, we only report the results of a length-corrected model by taking the residuals of a mixed-effects model that had 1/RT as the response variable, word length as a fixed effect, and a by-subject and by-items intercept. This region only showed a main effect of condition: the predicted noun was read faster than the unpredicted one; Coef = 0.03, $SE = 0.02$, $t = 2.18$.

4 Conclusions

Our study showed longer RTs at the unpredicted determiner (numerically) and at the noun (significant), which is consistent with the results from the literature (Van Berkum et al., 2005). There were no significant interactions between reading skills or working memory and condition, probably because the experimental sentences were too short and simple.

The novel finding in our study is that readers with less cognitive control were more affected by surprising content, namely, a determiner such as *seine* (feminine)

[1] Even though 4 participants performed poorly in the mathematical task of the operation span test (with less than 0.75% accuracy), including them did not affect the results concerning working memory and its interaction.

in 4 (repeated here as 5) that does not match the expected (masculine) gender according to the predictions for the upcoming noun (masculine: *Offen*). The longer RTs of low cognitive control readers can be explained by their increased difficulties in overcoming the mismatch between predictions and bottom-up evidence, that is the prediction error (see: Egner, Monti, & Summerfield, 2010). The results suggest that cognitive control modulates the ability to suppress irrelevant predictions, in this case the ability to inhibit the predicted gender form when it is not supported by evidence.

(5) a. Der Bäcker schob den Teig in **seinen**
The baker put the dough in **his.masc**
Ofen und wartete.
oven and waited

b. Der Bäcker schob den Teig in **seine**
The baker put the dough in **his.fem**
Mikrowelle und wartete.
microwave and waited

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