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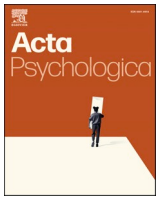

Register and morphosyntactic congruence during sentence processing in German: An eye-tracking study

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ABSTRACT

In the present study, we used eye-tracking to investigate formality-register and morphosyntactic congruence during sentence reading. While research frequently covers participants' processing of lexical, (morpho-)syntactic, or semantic knowledge (e.g., operationalized by means of violations to which we can measure responses relative to felicitous stimuli), less attention has been devoted to the full breadth of pragmatic and context-related aspects. One such aspect is sensitivity to formality-register congruence, i.e., the match or mismatch between the register of a target word and the formality conveyed by the (linguistic) context. In particular, we investigated how congruence of linguistic register with context formality, as well as its interplay with morphosyntactic knowledge, may unfold during reading and be reflected in eye movements. In our study, 40 native German speakers read context sentences conveying a formal or informal situation, and a target sentence containing a high- or low-register verb (e.g., Engl. transl. *The policeman detained the activist* vs. *The policeman nabbed the activist*) which matched or mismatched the formality of the preceding context sentences. We additionally manipulated subject-verb agreement, with either a match (see examples above) or a mismatch thereof (e.g., Engl. transl. **The policeman detain the activist*; **The policeman nab the activist*). We predicted that a violation of formality-register congruence would be reflected in longer reading times at the verb and post-verbal object region, as this would be in line with previous research on context violations (e.g., Lüdtke & Kaup, 2006; Reali et al., 2015; Traxler & Pickering, 1996). We found effects of morphosyntactic congruence on late processing stages at the verb and on earlier processing stages at the post-verbal object region. As far as formality-register congruence is concerned, only late (in total reading time analysis, in the post-verbal object region) and subtle effects emerged. The results suggest that, compared to morphosyntactic violations, formality-register congruence effects emerge quite subtly and slowly during reading.

1. Introduction

In the last three decades, psycholinguistic research has increasingly taken into account the pragmatic interpretation of a sentence as well as the influence of broader contextual aspects when studying language comprehension. It has become gradually clear that different sources of information are rapidly integrated during sentence processing, such as animacy (Trueswell et al., 1994), thematic fit (Ferretti et al., 2001; McRae et al., 1998), morphosyntactic structure (Pearlmutter et al., 1999; Tanner & Van Hell, 2014), and a speaker's informative intentions (Ronderos et al., 2024; Ronderos & Noveck, 2023), among others. For instance, in a study by Pearlmutter et al. (1999), subject-verb agreement mismatches (e.g., *The key to the cabinet were rusty from many years of disuse*) and apparent local number mismatches (e.g., *The key to the cabinets was rusty from many years of disuse*) both rapidly disrupted comprehension, albeit with slightly different eye-tracking patterns. Violations of syntactic constraints are also known to elicit rapid brain responses (see, e.g., Hagoort et al., 1993) such as the P600, a late positive-polarity event-related potential (ERP) component, peaking around 600 ms after the display of subject-verb agreement violations (e.g., "are" in a sentence such as *The spoilt child are throwing the toy on the ground*, Hagoort et al., 1999, p. 287). Generally, the role of broader language

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knowledge emerged as relevant for real-time ambiguity resolution. Furthermore, a rapid influence of expectancy on sentence processing was famously based on ERP evidence by Kutas and Hillyard (1980), who found that the amplitude of the N400 (a negative-going ERP component peaking around 400 milliseconds post-stimulus, interpreted as a detector of lexical-semantic anomalies) was larger for semantically incongruent (vs. congruent) words within the sentence context (e.g., "socks" at the end of the sentence *He spread the warm bread with*…, relative to ``butter", Kutas & Hillyard, 1980, p. 203).

Several factors influencing sentence comprehension have been identified thus far. Prior research has shown that (visual) context information is combined with – and modulates – real-time processing of various information sources, such as syntactic constraints (e.g., Chambers et al., 2004; Tanenhaus et al., 1995), affordances of the referent (Chambers et al., 2002), thematic role assignment (Knoeferle et al., 2005). Real-time effects of the comprehender's *offendedness* with regards to taboo words and the level of surprise with the speaker's utterance emerged in an eye-tracking study during reading (Christianson et al., 2017). Theoretical frameworks have progressively included the role of individual characteristics in the interpretation of the context. For instance, the social Coordinated Interplay Account (sCIA) (Münster & Knoeferle, 2018) accounts for how speaker and listener characteristics, as well as the non-linguistic context and world knowledge, can influence the comprehender's expectations and interpretation of the context.

One aspect which has received comparatively little attention but may enrich the extant accounts of intra-individual variability of language use is represented by register variation, although interdisciplinary research on register has recently shown how pervasive register-related phenomena are across different historical periods, text types, and linguistic domains (Lüdeling et al., 2022; Pescuma et al., 2023). Within the scope of the present paper, we define *register* as "[...] recurring variation in language use depending on the function of language and on the social situation" (Pescuma et al., 2023, p. 1). The focus of this definition is thus on intra-individual linguistic variation depending on situational-functional parameters (see also Lüdeling et al., 2022, for a broader overview on the topic). For instance, when referring to the event of a policeman or policewoman arresting an activist, one may use (or expect to hear) the high-register verb variant *inhaftierte* (Engl. transl. 'detained') in an official report, as opposed to *schnappte* (Engl. transl. 'nabbed') in an informal conversation with friends. Register-related phenomena have been alternately ascribed to lexical and pragmatic or rather to structural-syntactic aspects. An example is represented by studies on Japanese honorifics, which have alternately argued that the processing of register congruence can be best explained within a syntactic framework (e.g., Boeckx & Niinuma, 2004) or, rather, as mediated via socio-pragmatic factors (e.g., Cui et al., 2022). In the present work we investigate whether and how the (mis)match between context formality and linguistic register of the verb affects real-time sentence processing.

1.1. Sentence comprehension in context

It is known that non-linguistic factors, such as world knowledge, can influence sentence processing similarly to linguistic ones (e.g., semantics). For example, in an ERP study by Hagoort et al. (2004), an N400 effect was elicited both by semantic violations (*The Dutch trains are **sour** and very crowded*) and by world knowledge violations (*The Dutch trains are **white** and very crowded*), compared to the control condition *The Dutch trains are **yellow** and very crowded* (semantically and world knowledge-congruent; bold added for emphasis). Inferences about the social context of a communicative situation appear to be integrated in real-time sentence processing at very early stages, as evidenced for instance in a study by Van Berkum et al. (2008), where an early ERP effect was elicited by an incongruence between the speaker's social identity, as conveyed by her/his voice, and the message uttered (e.g., a young child, vs. an adult, uttering *Every evening I drink some wine before I go to sleep*). Crucially, the integration of relevant context information can overrule apparent lexical-semantic or plausibility violations, as shown in an EEG study by Nieuwland and Van Berkum (2006): here, in the presence of congruent context information, a sentence such as *The peanut was in love*, although violating a priori expectations regarding animacy, elicited a smaller amplitude in the ERP response as opposed to a semantically plausible condition, such as *The peanut was salted*. In an ERP study on the effects of genre on sentence processing, Blohm et al. (2017) found that participants who were aware of the poetic context of the experimental task showed a delayed P600 effect of non-standard morpho-phonological features, as these were "licensed" by the poetic instructions they received. This result suggests that context information is indeed taken into account in real-time processing of register variants.

While the evidence reported above shows that the integration of different sources of information contributes rapidly to successful sentence processing, so far relatively few accounts have explicitly considered the role of individual features of the speaker and the comprehender in language processing (see, e.g., the above-mentioned (social)Coordinated Interplay Account, Münster & Knoeferle, 2018) and a recent study on the comprehender's processing costs in relation to the informative intention that they attribute to the speaker (Ronderos & Noveck, 2023). A recent study by Sanders and de Bruin (2023) showed that, in a self-paced listening task, listeners displayed longer reaction times when non-native (relative to native) speakers uttered sentences containing grammatical violations (e.g., "Do you ***wanting*** anything?") or contextual formality errors (e.g., "Do you ***require*** anything?", in an informal context), compared to control sentences. This suggests that grammatical and/or contextual errors produced by non-native speakers take longer to process. Furthermore, recently, Troyer and Kutas (2020) have highlighted how individual differences in world knowledge (in their experiment, concerning the world of *Harry Potter*) can modulate the participants' N400 response to context manipulations. From several different perspectives, variability in terms of world knowledge and other background factors is increasingly becoming a research topic of its own in psycholinguistics. For instance, different degrees of literacy have been shown to modulate the time course of gaze, with an advantage in anticipatory eye movements towards correct targets for high-literacy (compared to low-literacy) individuals (Mishra et al., 2012). Similar patterns have been observed in bilinguals: within the context of a highly predictable sentence, L2 speakers of English were slower at directing their gaze towards target objects when presented in English, compared to L1 speakers of English, who relied more on phonological prediction (Ito et al., 2018).

1.2. Research questions

Our study investigated real-time processing of linguistic register variation by recording eye movements during sentence reading; specifically, we manipulated the degree of congruence of a target verb's linguistic register with respect to context formality. By means of a manipulation of formality-register congruence, as well as subject-verb morphosyntactic congruence, we aimed at investigating whether: (i) context formality information is rapidly integrated in real-time sentence comprehension, reflected in early gaze measures; (ii) the cognitive representations and mechanisms implicated in the processing of formality-register congruence are distinct from - or similar to - those underlying syntactic processing, as exemplified in this case by subject-verb morphosyntactic agreement. Shared or distinct mechanisms would be reflected, respectively, in additive or interactive effects (see, e.g., Hagoort, 2003; Sternberg, 1969). Gaining a more thorough understanding of the relation between register and grammar processing would allow to shed light on the nature of register phenomena. Namely, we investigated whether grammatical mismatches and register mismatches are detected similarly quickly, and whether the simultaneous manipulation of both factors would yield similar patterns in terms of effect magnitude and direction (e.g., comparable processing costs for register

and morphosyntactic mismatches) or, instead, a different picture reflecting reciprocal modulation between the effects (e.g., a more or less pronounced register mismatch effect in the presence of a morphosyntactic mismatch; (see Hagoort et al., 1993, for a similar logic concerning interaction effects in neural evidence). In order to habituate participants to the degree of context formality, thus possibly facilitating mismatch detection, the presentation of the stimuli was blocked (see Pfabigan et al., 2014, for some evidence on differences in ERPs between blocked and mixed presentation), such that a formal context block was followed by an informal context block (block order was counterbalanced across experimental lists). Participants were not informed about the blocked presentation. Additionally, in exploratory analyses, we investigated whether variability in the perceived degree of formality could play a role in real time processing of the stimuli.

2. Experiments

2.1. Methods

2.1.1. Participants

Eye movements were recorded monocularly from a group of 40 German native speakers (36 F, 4 M), between the ages of 18 and 30 (age $M = 23.32$, $SD = 2.74$). A power analysis conducted based on the pilot stimuli (see Supplement B.1) indicated that testing a minimum of 30 participants would achieve a power greater than 80 % for detecting the main effects. All participants were university students residing in the Berlin-Brandenburg area, and they received 11 Euros for their participation. They had not acquired any other language than German before the age of 6 years, with no cognitive or reading disabilities, as well as normal or corrected-to-normal vision. Participants not meeting these requirements were not allowed to sign up for participation in the study. Three of the participants who were tested were subsequently excluded from analysis due to failure to meet our attention check criterion, according to which a minimum of 75 % of the comprehension questions needed to be answered correctly in order for a participant's dataset to be included in the analysis. This left us with a final sample of $N = 37$ (33 F, 4 M; age $M = 23.35$, $SD = 2.80$). No participants who had taken part in the pilot study were included in the main study.

2.1.2. Stimuli and design

The experimental set included 32 critical and 56 filler items. Filler items were merely used as distractors and for attention checks (see below in this Section), and did not contribute to the statistical analysis of the results. Each experimental item comprised two context sentences and a target sentence. All target sentences in the critical items featured a subject-verb-object (SVO) sentence structure, with an animate subject noun phrase in the masculine gender[1] (*NP1*; e.g., *Der Polizist*, Engl. transl. 'The policeman'), a verb in the third singular German past simple (e.g., *inhaftierte*, Engl. transl. 'detained', high register, or *schnappte*, Engl. transl. 'nabbed', low register), and a direct (animate) object noun phrase (*NP2*; e.g., *die Aktivistin*, Engl. transl. 'the activist', feminine). A pair of context sentences preceding each target sentence set the tone for context formality, conveying a formal or informal social situation (see Table 1 caption). This permitted the manipulation of context formality-register congruence (match vs. mismatch) and counterbalancing. While morphosyntactic matches featured a correctly inflected verb in the third person singular (see above), morphosyntactic mismatches featured an infinitive form of the target verb (e.g., *inhaftieren, schnappen*), hence violating number agreement between the verb and the subject.

Web-based ratings for the degree of formality of context and target sentences were obtained from separate groups of participants and guided the construction and selection of the final stimulus set (for details on the rating procedures, see Section 2.1.3). Similar to the critical items, filler items comprised two context sentences followed by a "target" sentence. However, target sentences of filler items featured a less constrained structure and no manipulation of formality-register congruence or subject-verb agreement (e.g., *Nach dem Konzert der Sängerin gab es eine Meet-and-Greet-Session hinter der Bühne. Der Fan beteuerte: Wir haben dich so angefeuert.*; Literal Engl. transl.: 'After the concert of the singer, was there a meet-and-greet session backstage. The fan declared: We have so cheered for you.'; Free Engl. transl.: 'After the singer's concert, there was a meet-and-greet session backstage. The fan declared: We were so cheering for you.'). A small proportion (25 %) of filler items featured a manipulation of either formality-register congruence or subject-verb agreement in one of the context sentences. This was done in order to prevent strategies to discriminate critical vs. filler items merely based on the presence of register or subject-verb agreement violations. 75 % of all filler items were followed by simple yes/no comprehension questions, serving as an attention check.[2] We adopted a 2×2 experimental design (two factors: formality-register congruence and subject-verb morphosyntactic congruence, with two levels each: match and mismatch). Within each formality block, the order of items was pseudorandomized, and items were assigned to experimental lists according to a Latin square design.

2.1.3. Offline formality ratings

Web-based formality rating pretests were run in order to assess the degree of perceived formality of the context and target sentences. German native speakers aged 18–31 were recruited and compensated through Clickworker, and responded to a survey hosted on PCIbex (Zehr & Schwarz, 2023). These participants were distinct and independent from the sample recruited for the eye-tracking experiment.

Two different pretests were run for context sentence formality and target sentence formality. Across both iterations of the target sentence formality pretest, 62 participants (31 per iterations) took part; we were able to use data from 52 participants (30 + 22; 9 were excluded due to failure to meet monolingualism or age criteria; one participant was excluded as they displayed an identical pattern of responses across questions). Across both iterations of the context sentence formality pretest, 63 participants (31 in the first iteration, 32 in the second) took part; we were able to use data from 57 participants (28 + 29; 6 were excluded due to failure to meet our attention check criteria). In both target and context sentence formality pretests, participants were asked to rate the formality of the stimuli on a scale from 0 (very informal) to 50 (very formal). Having a broader rating scale than the more common 5- or 7-point Likert scale allowed formality to be more gradually rated and spread across a larger number of points, such that we could treat the ratings as a continuous variable (see, e.g., Harpe, 2015). A 10-point difference between the average ratings for the formal and informal variants of each item was minimally required for item suitability. Two iterations of both pretests were required in order to reach satisfactory formality ratings (see Supplement A.1, Supplement C.2). We retained well-rated items from the first pretest iterations and replaced those which had not reached satisfactory ratings through the second iterations. Aggregating both datasets, we obtained satisfactory target sentence and context formality ratings for the final 32 critical items. As far as context formality ratings are concerned, the informal context sentence pairs received lower formality ratings (mean = 14.86; SD = 9.68; median = 13.25) than the formal context sentence pairs (mean = 35.81;

[1] A singular masculine subject noun phrase, in which the determiner (*der*) is expressed in the nominative case in German, was necessary in order to minimize ambiguity as to the noun's thematic role assignment within the sentence. This would have instead been ambiguous for a feminine noun phrase, as the determiner *die* would not be inflected differently in the nominative compared with the accusative case.

[2] Example of a filler comprehension question (yes/no answer): *Hat der Fan die Unterstützung beteuert?*; Literal Engl. transl. 'Has the fan the support declared?'; Free Engl. transl.: 'Did the fan declare his support?'.

Table 1
Illustration of four conditions, and their counterbalancing version, for a critical item. Formal context example: *Während der gestrigen Ausschreitungen waren die Einsatzkräfte gnadenlos. Die Polizeidirektorin referierte die Rivalität:*, Literal Engl. transl. 'During the yesterday's riots, were the emergency forces merciless. The police director lectured the rivalry:'; Free Engl. transl. 'During yesterday's riots, the emergency forces were merciless. The police director lectured the rivalry:'. Informal context example: *Bei der Demo gestern war die Stimmung richtig heftig. Die Olle hetzte die Protestler:*, Literal Engl. transl. 'At the demo yesterday was the atmosphere really intense. The old woman$_{pej}$ stirred up the protesters:'; Free Engl. transl. 'The atmosphere at the demo yesterday was really intense. The old woman$_{pej}$ stirred up the protesters:'. Target sentence example: *Der Polizist inhaftierte* (high register)/*schnappte* (low register) *die Aktivistin*, Engl. transl. 'The policeman detained/nabbed the activist'. Glossing abbreviations: PAST-3SG = verb in the past tense, third person singular; INF = infinitive verb; pej = pejorative.

Condition	Formality-Register congruence	Morphosyntax congruence	Context	Target
1a. Full match	Match	Match	Formal	$inhaftierte_{PAST-3SG.formal}$
1b. Morphosyntax mismatch	Match	Mismatch	Formal	$inhaftieren_{INF.formal}$
2a. Formality-register mismatch	Mismatch	Match	Formal	$schnappte_{PAST-3SG.informal}$
2b. Full mismatch	Mismatch	Mismatch	Formal	$schnappen_{INF.informal}$
1a'. Full match	match	match	informal	$schnappte_{PAST-3SG.informal}$
1b'. Morphosyntax mismatch	Match	Mismatch	Informal	$schnappen_{INF.informal}$
2a'. Formality-register mismatch	Mismatch	Match	Informal	$inhaftierte_{PAST-3SG.formal}$
2b'. Full mismatch	Mismatch	Mismatch	Informal	$inhaftieren_{INF.formal}$

SD = 9.45; median = 37.50), with an average difference of 20.95 points between conditions. As far as target sentence formality ratings are concerned, the informal target sentence pairs received lower formality ratings (mean = 16.67; SD = 10.28; median = 15.23) than the formal target sentence pairs (mean = 32.06; SD = 9.76; median = 32.80), with an average difference of 17.56 points between conditions.

2.1.4. Procedure

Participants' eye movements were recorded monocularly using an EyeLink 1000 Plus desk-mount eye-tracker (SR Research, Mississauga, Ontario, Canada). Before the experiment started, tracker calibration and validation were performed. A nine-point calibration procedure was carried out; following validation, the procedure was accepted only if the maximum error was smaller than or equal to 0.50 degrees of visual angle. Calibration and validation were performed again after each experimental block, and could be re-performed between trials if deemed necessary due to progressive loss of tracking accuracy over time. Participants were instructed to silently read the stimuli for comprehension and to respond to occasional comprehension questions pressing the Yes and No buttons on the provided Cedrus button box. A short round with two practice items was administered at the beginning of the experiment. All experimental stimuli comprised consecutive displays: Participants were shown the first context sentence, followed by the second context sentence, and finally the target sentence (see Fig. 1). Monospace font *Consolas*, font size 30 was used for the display of the stimuli. Participants sat approximately 90 cm away from the display and rest on a head- and chinrest. They were instructed to move as little as possible during the experiment. They could proceed to the next sentence or trial through button press whenever they were done reading, and a time-out was set for each screen when over 8000 ms elapsed, represented by a feedback message (Engl. transl.: "You took to long to respond. Please be faster!"). The experiment required approximately 40 min for completion, including three short breaks between experimental blocks in order to minimize eye strain.

2.1.5. Hypotheses

We predicted longer reading times at the verb region for register-mismatching verbs (i.e., a high-register target verb following informal-situation context, and vice versa) and for morphosyntactically mismatching verbs (i.e., infinitive forms). We concentrated on three eye-tracking reading measures to examine various temporal processing stages. These measures were: *first-pass reading time*, the sum of the duration of all fixations performed within the first pass on an interest area before leaving it, reflecting early stages of lexical processing; *regression path duration*, the sum of the duration of all fixations performed on an interest area before exiting it rightward, including regressions to previous areas, and reflecting sentence integration processes; and *total reading time*, the sum of the duration of all fixations performed across all runs on an interest area, a cumulative and late measure reflecting post-lexical integration.

We anticipated an increase in these measures during processing of mismatches, reflecting the processing costs associated with incongruent formality information and incongruent morphosyntactic information, respectively. Prior research, such as Pearlmutter et al. (1999), observed eye-tracking effects of syntactic incongruence during processing of up to several words after the target region. The fact that such effects often emerge after the target word is also highlighted by Clifton and Staub (2011) in their chapter on syntactic influences on eye movements. Based on such findings and evidence, we expected that effects might emerge up to the spillover region (NP2) where, for instance, integration costs can be observed following morphosyntactically-mismatching verbs.

Our hypotheses can be connected with the sCIA framework (Münster & Knoeferle, 2018), whereby the unfolding of formality-register and morphosyntactic congruence processing during sentence reading could be divided into three processing steps. The verb would first be interpreted (**Interpretation**, $step_i$) based on the comprehender's world knowledge, expectations and linguistic constraints. The comprehender would then anticipate how the sentence might unfold, based on $step_i$ (**Utterance-mediated attention**, $step_{i'}$). Finally, the comprehender will integrate the verb in the target sentence with the context information (**Integration**, $step_{i''}$); this might then result in longer reading times for formality-register mismatching verbs. Depending on the characteristics of the comprehender (referred to as *ProCom* in Münster & Knoeferle, 2018), in this case reflecting her/his knowledge of morphosyntactic and register congruence, as well as her/his social expectations (ant_s^p),[3] the processing of formality-register and morphosyntactic congruence may occur differently. For instance, it is possible that morphosyntactic congruence will produce an earlier and more pronounced effect, potentially eclipsing the effects of formality-register congruence. While we do not focus on the sCIA implementation here, this is a focal point in our future research. For a schematic illustration of how the sCIA framework may be applied to the current study, see Pescuma et al. (2023, Figure 11).

Overall, we predicted that this study, as well as the previously conducted pilot study, would help define the relationship between these effects. In particular, we investigated the effects of register and morphosyntactic congruence, as well as their potential interaction. Our hypothesis concerning the interplay of these effects was guided by a rationale similar to Hagoort et al. (1993). According to this framework, processes relying on separate cognitive mechanisms and representations

[3] $ant_s^p a$ tracks expectations; s stands for 'social', and it is assigned a certain probability (p) ranging between 0 and 1.

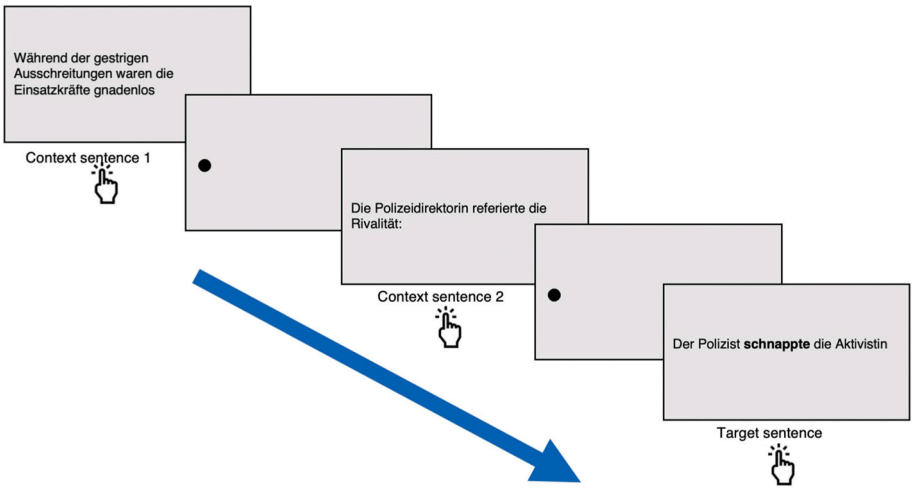

Fig. 1. Example of the presentation of an experimental trial. The first context sentence, the second one, and the target sentence were presented sequentially and individually. The target word is marked in bold for illustration purposes only. Font and layout adapted for illustration purposes.

would be reflected in distinct brain correlates, while processes sharing cognitive underpinnings would be characterized by a reciprocal modulation of brain correlates. Hence, in our eye-tracking study, we hypothesized that, if found, interactive effects of register and morphosyntactic congruence processing might indicate shared underlying cognitive mechanisms and representations, while additive effects might indicate distinct mechanisms and representations.

Finally, exploratory analyses carried out on the pilot data collected before the main experiment revealed a main effect of some of the (target and/or context sentence) formality ratings on gaze patterns. This informed our analysis plan, leading to the addition of formality rating measures as covariates in the statistical models in both studies presented here.

2.2. Analysis[4]

Eye movement data were preprocessed using Data Viewer (SR Research). Fixations shorter than 80 ms were merged with other fixations within a maximal distance of 0.50 degrees; remaining fixations below 80 ms and above 1000 ms were excluded before eye-tracking reports were generated. Linear mixed models were fitted using *R* (R Core Team, 2021) and the package *lme4* (Bates et al., 2014). Analyses were conducted on two predefined areas of interest: the verb (target region, e.g., *schnappte*) and the NP2 (object, post-target noun phrase, e.g., *die Aktivistin*). The predictor term in each model comprised an interaction (and main effects) of *formality-register congruence*morphosyntactic congruence*, as well as the addition of *average target sentence formality ratings* and *average context formality ratings* as covariates. The latter were included in the models following exploratory analyses performed on the pilot (see Supplement A). Formality-register and morphosyntactic congruence were sum-contrast coded (for both factors: match: 1; mismatch: −1), while the ratings were treated as continuous variables (on the treatment of rating values as continuous see Harpe, 2015). The dependent variables in our models were the above-mentioned eye-tracking measures, indexing different stages of processing (see, e.g., Rayner, 1998, 2009; Juhasz & Pollatsek, 2011; Clifton et al., 2016): *first-pass reading time*, *regression path duration*, and *total reading time*. Following a Box-Cox test (using the function *boxCox* within the R package *car*), all three eye-tracking measures were log-transformed before being included in the models in order for the residuals to be approximately normally distributed. For visualization purposes, model estimates of the eye-tracking measures were then exponentially back-transformed for the scale to be more intelligible (see Section 2.3). As the datasets obtained from the main study comprised a greater number of observations than the pilot study, the model selection procedure was further refined compared to the pilot study (see Supplement A.2). While the fixed effects structure was the same as in the pilot data analysis, the random effects structure (RES) could be expanded, given the greater *N*, so that it would originally include, for all models, the following random intercepts and slopes:

```
(1 + formality_register_congruence * morpho-
syntactic_congruence | participant) +
(1 + formality_register_congruence * morpho-
syntactic_congruence | item)
```

Prior to any significance test of the fixed effects, the RES of each model was blindly assessed and, when necessary, reduced to a simpler structure (see Bates et al., 2015) via inspection of the RES covariance matrix (using the function *VarCorr* from the R package *lme4*) and through a principal component analysis of the RES covariance matrix (via the function *rePCA* from the R package *lme4*). Random effects not contributing or only minimally contributing to the variance of the model were thus simplified or removed. Before fitting any analysis models, we inspected the normality of the distribution of our data by means of a Q–Q plot, using the *qqnorm* function from the R package *stats*). As the data were not normally distributed, we ran a Box Cox test (see Section 2.2), which indicated that a log transformation of our dependent variables should be performed. The β values reported from our models (see 2.3) are thus expressed on a log scale. Furthermore, we report effect sizes in the form of Cohen's *d* values, calculated through the *lme.dscore* function of R package *EMAtools* (Kleiman, 2017) The model outputs are plotted following an exponential back-transformation for visualization purposes, to better convey the time scale (*y* axis) of the effects.

2.3. Results

According to our Hypotheses (see Section 2.1.5) and based on our pilot findings, if processing of morphosyntactic congruence and/or formality-register congruence occurred early and rapidly during sentence reading, we expected an increase in first-pass reading measures for mismatches vs. matches at the critical (verb), potentially continuing into the post-critical object region. Incremental and later processing of morphosyntactic congruence and/or formality-register congruence

[4] Full datasets and scripts can be downloaded from the project's OSF repository.

would instead result in an increase in later reading measures (regression path duration and total reading time) at the critical (verb) and/or post-critical object region. Results of our analyses on first-pass, regression path duration and total reading time are presented for both regions of interest (verb and NP2).

In our **verb region analysis**, we did not find effects on early processing measures (i.e., on first-pass) of register or morphosyntactic congruence. First-pass analysis of the verb region revealed instead a main effect of an exploratory covariate, average target sentence formality ratings; longer durations were associated with higher formality ratings (β=0.007, t = 3.81, p<$_0$.001, d = 0.23; Fig. 2 **[a]**).

Regression path duration analysis of the verb region also showed a similar main effect of average target sentence ratings (β=0.007, t = 3.69, p < .001, d = 0.22; Figures are provided in Supplement C.3, see Fig. C.8 **[a]**).

Total reading time analysis of the verb region (Fig. 2 **[b]**) revealed a main effect of morphosyntactic congruence (subject-verb agreement, mismatches vs. matches; β=0.06, t = 2.42, p = .02, d = 0.86), as well as a main effect of average target sentence ratings (β=0.01, t = 4.20, p < .001, d = 0.26; Fig. 2 **[b]**): Morphosyntactically mismatching verbs yielded longer total reading times, as predicted (see Section 2.1.5); longer verb total reading times were also observed for verbs in target sentences with higher formality ratings, one of our exploratory covariates.

In the **analysis of the post-verbal object region**, the effects of morphosyntactic congruence emerged in earlier measures and more robustly. First-pass analysis of the NP2 region revealed a main effect of morphosyntactic congruence, albeit with a direction opposite to that predicted, with longer first-passes following matching (vs. mismatching) verbs (β= − 0.07, t = −2.61, p = .014, d = −0.94; Fig. 3 [a]). This pattern may be explained by the complexity of mental calculations entailed in the integration processes required by our manipulations. Indeed, when running additional analyses, we found that when excluding first-passs followed by "regressions out" (e.g., regressive eye movements launched from NP2 to prior interest areas), this effect disappeared. When the analysis included only first-passs followed by regressions out, we observed an interactive pattern between register and morphosyntactic congruence. The reversal of the morphosyntactic congruence effect on NP2 first-pass occurring only when regressions out are included aligns with results from an eye-tracking study by Pearlmutter et al. (1999). According to this study, to Rayner and Sereno (1994) and to Altmann et al. (1994), when readers encounter difficulty processing a certain region, they may either spend more time fixating it or regress out of it. Regression path duration analysis of the NP2 region showed a main effect of morphosyntactic congruence. In line with patterns of overt syntactic violations (e.g., Clifton & Staub, 2011; Pearlmutter et al., 1999), regression path durations were longer for nouns which followed morphosyntactically mismatching (vs. matching) verbs (β=0.063, t = 2.69, p = .01, d = 0.89; Figures are provided in Supplement C.3, see Fig. C.8 **[b]**). Finally, total reading time analysis of the NP2 region revealed a subtle main effect of formality-register

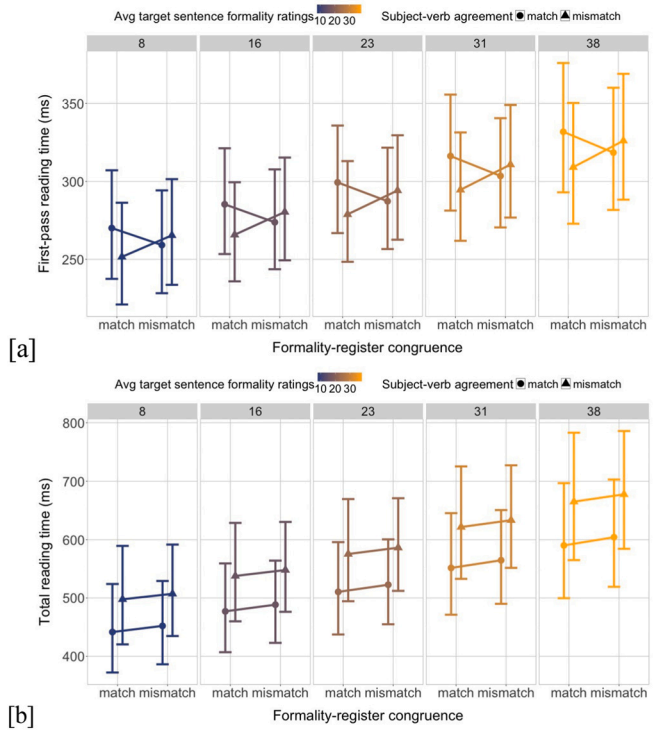

Fig. 2. Main study. **[a]** Verb first-pass as a function of formality-register congruence, subject-verb morphosyntactic congruence, and average target sentence formality ratings. Main effect of average target sentence formality ratings: Verbs in more formally rated sentences yielded longer first-passes. **[b]** Verb total reading time as a function of formality-register congruence, subject-verb morphosyntactic congruence, and average target sentence formality ratings. Main effects of mosphosnyntactic congruence and of target sentence formality ratings: Morphosyntactically mismatching verbs and verbs in more formally rated sentences yielded longer total reading times. Color key: average ratings of target sentence formality, on a scale from 0 to 50, plotted as continuous. Panels exemplify portions of the distribution of the average formality ratings. Error bars: 95 % confidence intervals.

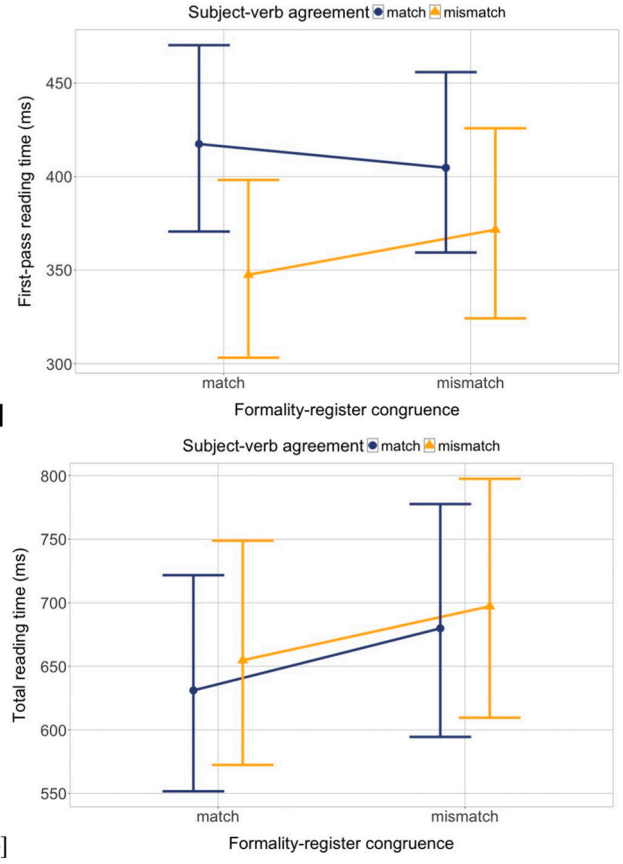

Fig. 3. Main study. **[a]** Post-verbal object noun (NP2) first-pass as a function of formality-register congruence and subject-verb morphosyntactic congruence. Main effect of subject-verb morphosyntactic congruence: Agreement-congruent verbs yielded longer first-passes. **[b]** Post-verbal object noun (NP2) total reading time as a function of formality-register congruence and subject-verb morphosyntactic congruence. Main effect of formality-register congruence: Register-mismatching verbs yielded longer total reading times. Error bars: 95 % confidence intervals.

congruence, in the predicted direction: Longer object total reading times were observed following register-mismatching (vs. matching) verbs (β=0.034, $t = 2.05$, $p = .04$, $d = 0.12$; Fig. 3 **[b]**). No effects of the interaction, nor of context or target formality ratings emerged from this analysis (thus not represented in the figures).

3. Discussion

While the object of our investigation was the processing of both register and subject-verb morphosyntactic congruence, we mainly observed effects of subject-verb morphosyntactic congruence. In line with extant research on syntactic processing (Pearlmutter et al., 1999; Pickering & Traxler, 1998), mismatches generally yielded longer reading times. Such effects, as well as those of average target sentence formality ratings (exploratorily added as covariates, see Section 2.1.4) emerged much more markedly and on an earlier region (i.e., the verb) than those of formality-register congruence. In contrast to the pilot study (see Supplement A), in the main study we found no evidence of an interaction effect between the two factors. The core difference between the pilot study and the main experiment lies in the sample size ($N = 8$ vs. $N = 37$). Hence, we attribute these contrasting findings primarily to such differences in sample size.

Effects of morphosyntactic congruence emerged at the verb region on total reading time, a measure associated with a late processing stage. At the post-verbal object region, we observed effects of morphosyntactic congruence on first-pass, a measure associated with an early processing stage. As noted in the Results Section 2.3, the effect of morphosyntactic congruence on NP2 first-pass was reversed, but this only occurred when regressions out were present. According to Pearlmutter et al. (1999); Rayner and Sereno (1994); Altmann et al. (1994), this might index added cognitive load, as some readers might regress away from a region they are finding difficult to process, presumably to re-read the left context rather than fixate it for a longer period of time. This could indicate they are attempting to verify the interpretation by re-reading the left context after encountering a difficult-to-integrate word.

Furthermore, as noted, our analysis of first-pass and total reading time at the verb region showed an effect of the exploratory covariate, average target sentence formality ratings. This finding is interesting and could inform future research on real-time processing of formality; however, our fully counterbalanced design and the exploratory nature of the covariate did not warrant its inclusion in our models as part of the interaction term.

Effects of formality-register congruence were subtle and could only be observed at the post-verbal object region in total reading time. The time course with which both effects appear to have unfolded may suggest that morphosyntactic mismatches are quite salient relatively early on during sentence processing. By contrast, more nuanced violations - rather pertaining to world knowledge and lexical-semantic knowledge – such as formality-register mismatches – emerge more subtly and require longer to be processed. Indeed, recent studies (Patarroyo et al., 2022; Yurchenko et al., 2023) have shed some light on the similarities in the processing of register and lexical-semantic mismatches. However, the relationship between register and with subject-verb morphosyntactic mismatches has thus far received less attention, with the exception of a recent preprint by Masullo et al. (2023). In an acceptability judgment task, the authors found that register significantly impacted the detection of subject-verb agreement violations, with errors more accurately identified in low-register contexts. The authors furthermore observed that the pattern of the effect varied among monolingual, bilingual, and bidialectal participants.

The finding of a late effect of formality-register congruence only in the post-verbal object region indicates that such processing might require longer to unfold, compared to violations of morphosyntactic knowledge. In spite of the different factors which were manipulated, this finding is in keeping with previous research. For instance, in an eye-tracking study, Warren et al. (2008) investigated how readers processed sentences describing possible and impossible events within varying contexts. The results showed that the initial detection of the impossibility of an event was detected relatively independently of context information; the effect of plausibility given the context did not emerge early or rapidly, but rather at late processing stages in the post-critical region. This suggests that while initial detection of an impossible event is context-independent, the integration of plausibility information occurs more slowly and at later processing stages. In line with such findings, our results suggest that – at least in our study, featuring a manipulation of both morphosyntactic and register-related factors – formality-register congruence information is not very rapidly integrated. This might imply that register processing is delayed until morphosyntactic processing is completed, thus taking longer to unfold in real-time processing.

A further reason for the somewhat later effects of register-congruence might be the pragmatic nature of the formality-register congruence manipulation. Similar evidence on partially incremental processing of pragmatic implicatures was found with respect to the interpretation of quantifiers (see Urbach & Kutas, 2010; Huang & Snedeker, 2009, for ERP and eye-tracking evidence, respectively).

Additionally, the pattern of results observed in our study yields two further considerations on the differences between morphosyntactic and register processing, which future research may need to consider. First, one might want to take into account differences in the probabilistic nature of processing morphosyntactic and register incongruence. Morphosyntactic incongruence, once detected in the form of a mismatch between the subject and verb inflection, is absolute, in that it violates syntactic knowledge. By contrast, incongruence in the formality of a situation and language register seems to be more variable. It is thus possible that the relative delay in formality-register congruence effects comes from greater real-world variability for this congruence manipulation compared with the morphosyntactic manipulation. Second, future research will want to consider differences in the extent to which these two types of congruence manipulations are taxing for working memory. Establishing morphosyntactic congruence in the present experiment requires integrating the subject with the neighboring verb —- that is, a local violation needs to be detected. By contrast, establishing formality-register congruence requires participants to draw on their working memory of a prior short discourse. This process may be subject to greater variability, leading to increased temporal variability as to when participants establish such incongruence, compared with morphosyntactic congruence between neighboring sentence constituents.[5]

The cognitive effort required to maintain information related to distant and complex contexts may stem from the challenge of processing words or phrases that are far apart yet interconnected. Shorter dependencies are easier to handle, whereas longer ones increase processing difficulty. Although in a different field, this concept aligns with research on locality and syntactic complexity, which shows that cognitive load is increased when processing long-distance syntactic dependencies compared to shorter ones (see, e.g., Lewis et al., 2006; Gibson, 1998, 2000).

Finally, regarding the potential consequences of the sCIA (see Section 2.1.5), we note that the existing account may need to be refined to more clearly specify the parameters *ProCom* (comprehender features) and ant_s^p (probability of social expectations), ensuring they better capture the variability in real-time processing of morphosyntactic and formality-register (mis)matches. We aim to address these revisions in future research.

[5] However, we note that a similar pattern incremental and delayed effects was found in an eye-tracking reading study on Japanese honorifics where a manipulation of formality-style congruence was performed within the same sentence (Pescuma et al., 2024).

4. Conclusions

With our investigation, we aimed to shed light on two questions: (i) Whether formality-register congruence effects would emerge rapidly, i.e., in early gaze measures; (ii) whether cognitive mechanisms permitting the processing of formality-register congruence are distinct or shared with those underlying the effects of morphosyntactic knowledge during language processing. The findings from the main study suggest that processing of formality-register congruence unfolds quite slowly during sentence comprehension. We only observed formality-register congruence effects after the critical word was read, likely while integration with the preceding context was still ongoing. Such delay might reflect an increased cognitive demand in maintaining a complex model of the previous linguistic context in one's working memory (see final considerations in the Discussion, Section 3). Overall, while a definitive answer as to whether morphosyntactic and register processing rely on shared cognitive mechanisms cannot be provided yet, the two types of processing appear to unfold at a different pace during sentence reading. Findings of subtle, late-emerging effects of formality-register congruence may suggest that a longer spillover region could favor a longer and more robust observation of register effects unfolding (see, e.g., Pearlmutter et al., 1999, in which effects of syntactic violations on eye movements during reading were observed also following the critical region). We acknowledge that the short spillover region (the object noun phrase, NP2), as well as the inherently different (local or short-distance vs. global or long-distance) nature of the two experimental manipulations, might constitute limitations of this experiment. At the same time, due to the design of the experiment, we cannot tease apart how different working-memory requirements contributed to the results from how the nature of the congruence type contributed.

In conclusion, in the present study, we have begun uncovering the nuanced nature of real-time processing of register congruence, highlighting differences regarding the temporal unfolding of morphosyntactic processing. Ongoing and future studies will further inform psycholinguistic research on the - still relatively underinvestigated - topic of register, providing evidence with respect to the nature of register phenomena as compared with other better explored linguistic aspects.

Ethics and consent

Studies involving human participants were approved by the Ethics Committee of the Deutsche Gesellschaft für Sprachwissenschaft (DGfS, #2019-07A-200424). The participants provided their written informed consent to participate in our studies.

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CRediT authorship contribution statement

Valentina N. Pescuma: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Katja Maquate:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Camilo R. Ronderos:** Writing – review & editing, Software, Resources. **Aine Ito:** Writing – review & editing. **Pia Knoeferle:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

None.

Statement on the use of generative AI

During the preparation of this work the author(s) used ChatGPT only in order to improve the readability of originally written material, not to generate new material. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2024.104547.

Data availability

Datasets and analysis scripts are available at https://osf.io/gevmq/.

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