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Abstract

The present study investigated the time-course of semantic integration in auditory compound word processing. Compounding is a productive mechanism of word formation that is used frequently in many languages. Specifically, we examined whether semantic integration is incremental or is delayed until the head, the last constituent in German, is available. Stimuli were compounds consisting of three nouns, and the semantic plausibility of the second and the third constituent was manipulated independently (high vs. low). Participants' task was to listen to the compounds and evaluate them semantically. Event-related brain potentials in response to the head constituents showed an increased N400 for less plausible head constituents, reflecting the lexical-semantic integration of all three compound constituents. In response to the second (less plausible) constituents, an increased N400 with a central-left scalp distribution was observed followed by a parietal positivity. The occurrence of this N400 effect during the presentation of the second constituents suggests that the initial two non-head constituents are immediately integrated. The subsequent positivity might be an instance of a P600 and is suggested to reflect the structural change of the initially constructed compound structure. The results suggest that lexical-semantic integration of compound constituents is an incremental process and, thus, challenge a recent proposal on the time-course of semantic processing in auditory compound comprehension.

Keywords: cognition; language comprehension; lexical processing; compound word; semantic composition; conceptual combination; German; ERP; EEG

Introduction

The expressive power of human language is rooted partly in its infinite vocabulary, i.e. our ability to create new words. For example, A. A. Milne wrote in 1924 the children's poem *Twinkletoes*. If you are not familiar with twinkletoes, you can decompose the compound word into its constituents TWINKLE and TOES. You may then try to construct the meaning of the compound by combining the two constituents. Compounding is an important means of word formation available in most languages. It refers to the (recursive) structured combination of free morphemes into new lexical units (e.g. BATH+TOWEL+RACK). Compounding is restrictive and creative, i.e. it serves to specify a given word meaning, or it can evoke new meanings of a given word (Booij, 2002; Wiese, 1996; Downing, 1977). However, little is known about the cognitive-semantic processes that support compound constituent integration. Here, we are interested in the semantic integration within compounds (henceforth called *lexical-semantic integration*, as opposed to semantic integration on the sentence level) and, in particular, in the time-course of constituent integration during auditory compound comprehension.

Compounds were shown to be decomposed semantically during comprehension in the visual and in the auditory modality at least if they are semantically transparent. (The meaning of transparent but not of opaque compounds is related to their constituents; cf. ”blackbird” vs. ”black mail.”) That is, the meaning of each constituent is accessed during understanding a compound, presumably in order to integrate all constituent meanings. Sandra (1990) reported facilitated word recognition in Dutch, i.e. shorter reaction times for written compounds that were preceded by associatively related, written mono-morphemic nouns compared to compounds preceded by unrelated nouns. Similarly, Zwitserlood (1994) found priming effects for written mono-morphemic Dutch nouns that were preceded by compounds that contained a semantically related constituent. In a cross-modal priming experiment, Pratarelli (1995) used event-related brain potentials (ERPs) to investigate priming between pictures and acoustically presented compounds in English. The pictures names were compounds but participants did not have to name them. Pratarelli (1995) found a reduced ERP amplitude in response to the compound constituents, if they were semantically related to the picture name. Also, acoustically presented compounds were shown to prime semantically related written words in German by means of behavioural measures and ERPs (Wagner, 2003; Isel, et al., 2003). In sum, these priming effects suggest that each constituent is processed separately with regard to its meaning, if the compounds are semantically transparent.

When the constituents have been activated semantically a structured integration process appears to be necessary to construct the compound meaning (Gagné, & Spalding, 2009). A mere co-activation or association of the constituents is not sufficient because the so-called head constituent determines the morphosyntactic features (e.g. word class, number, or syntactic gender) and mostly also the semantic category of the whole compound (Selkirk, 1982; Williams, 1981). For example, a *bath towel rack* is a kind of rack, not a kind of towel or bath. That is, the head plays a central role regarding the make-up of compounds. In many languages such as English, German or Dutch compounds are right-headed, i.e. the right-most constituent is the head but compounds can be left-headed in other languages (e.g. French or Italian; Fabb, 2001). Head constituents are a plausible candidate for constituent integration because they usually determine the semantic category of the compound, i.e. the meaning of the head is modified by the non-head constituent(s).

Accordingly, it has been suggested that head constituents play a central role in the auditory processing of compounds (Isel, Gunter, & Friederici, 2003). In their prosody-assisted head-driven model, the authors suggest that the head constituent serves as an access code to the lexical entries of compounds. For German two-constituent compounds with a semantically transparent head, initial constituents were found to be activated only at the end of the head constituent. Importantly, Isel et al. did not find priming effects at an earlier position, namely at the boundary between constituents. This pattern of results suggests, firstly, that semantically transparent compounds are decomposed, i.e. the constituents are accessed separately. Secondly and importantly, since the priming effect was delayed, it was proposed that semantic access of non-head constituents is controlled by head constituents. That is, semantic access of non-head constituents is thought to *follow* the access of head constituents (p. 287, Isel et al., 2003). We will refer to this approach as the *delayed account* of constituent integration. The delayed account implies that semantic integration of compound constituents is also (possibly indirectly) controlled by head constituents because integration presupposes access of constituents or at least activation of constituents (cf. Van den Brink, Brown, & Hagoort, 2006). Hence, the delayed account leads to the testable prediction that semantic constituent integration should not occur before the head constituent is perceived. The present study set out to test whether lexical-semantic integration occurs only after the head constituent has been encountered.

One question that remains to be answered for the delayed integration account is how head constituents are detected, i.e. how they are distinguished from non-head constituents. One possibility is that the word boundary, i.e. the offset of the compound word is used to determine the head constituent. Word segmentation which signals word boundaries is a highly automatic and reliable mechanism (Brent, 1999; Norris, McQueen, Cutler, & Butterfield, 1997). An alternative may be that the head constituents have an internal cue themselves. It remains speculative whether prosody signals the constituent's head/non-head status but preliminary results suggest that this is the case (Koester, Gunter, & Friederici, 2005).

One might also wonder whether listeners can differentiate compounds and single nouns (non-compounds) in the first place. Vogel and Raimy (2002) reported that single nouns and initial compound constituents differ systematically in their prosody (mean duration and mean fundamental frequency). In the series of experiments described by Isel et al. (2003) it was suggested that the durational difference between single nouns and initial compound constituents can delay the semantic processing of initial compound constituents. Finally, Koester et al. (2004) reported that the contour of fundamental frequency begins to differ between single nouns and initial constituents 75–100 ms after compound onset which appears to modify the morphosyntactic compound processing. Thus, listeners can detect compounds early on during comprehension which is a prerequisite for the delayed integration account.

Similar to the delayed integration account, it has been suggested that semantic processing (constituent access and/or integration) occurs at a late stage in compound reading (see below; White, Bertram, & Hyönä, 2008; Inhoff, Radach, & Heller, 2000; Van Jaarsveld, & Rattink, 1988; but see Fiorentino, & Poeppel, 2007). Importantly, most studies that investigated compounds used two-constituent compounds. Obviously, integration is not possible during the initial constituent. Therefore, it is difficult to find out whether integration is a late process that has to await the head constituent or can begin before the head constituent is detected. One notable exception is the study by Inhoff et al. (2000) who examined the reading of German three-constituent compounds in sentences using eye tracking measures. Note that three- and four-constituent compounds are natural and commonly used in German (Fleischer, & Barz, 1995). In their eye tracking experiment, Inhoff and colleagues sometimes marked constituent boundaries, e.g. by interword spaces which is improper spelling for German. Whereas these spaces facilitated early processing stages (reflected in first fixation duration), they inhibited late stages (reflected in gaze duration). Inhoff et al. (2000) have argued that first fixation duration reflects constituent access which is facilitated due to the explicit marking. In contrast, the gaze duration measure includes late processes such as constituent integration (called conceptual unification) which was hampered by the improper spelling. Thus, it was argued that constituent integration takes place at a late processing stage.

In contrast to the delayed integration account, it is conceivable that lexical-semantic integration proceeds incrementally. That is, when the second constituent of a compound is perceived, integration begins as soon as its semantic information becomes available. The resulting representation can then be modified further (i.e. integrated) if another constituent is perceived until the compound can be conceptually unified when the head is perceived. Such an immediate integration account can be derived from the immediate use of lexical(-semantic) knowledge as shown in sentence processing (e.g. DeLong, Urbach, & Kutas, 2005; Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005; Wicha, Bates, Moreno., & Kutas, 2003). However, the available data on compound processing are in line with a delayed integration account (Isel et al., 2003) which might also be related to the fact that compounds do not have propositional content as sentences usually do.

The present study aims to investigate the time-course of semantic integration in auditory compound comprehension. Specifically, we want to answer the question of whether lexical-semantic integration is postponed to the occurrence of the head constituent in German compounds. To this end, we used semantically transparent three-constituent compounds which make it possible to examine whether integration begins before the head, namely during the second non-head constituent. In order to increase control over our stimuli we opted for the construction of compounds with the lowest possible frequency. Lowest frequency of the compounds was operationally defined as being not listed in the Celex database (Baayen, Piepenbrock, & Gulikers, 1995).[1] The combinations of first and second constituents were also not listed. The Celex database was chosen because it provides reliable information and is widely-used, thereby ensuring comparability with a wide range of psycholinguistic studies. Importantly, compounds that are not listed in Celex are highly unlikely to have a lexical representation of their own (Alegre, & Gordon, 1999) and, therefore, our stimuli need to be

[1]The fact that the compounds were not listed in Celex does not imply that the compounds are strictly novel. However, novelty itself is not relevant here; it is important that the compounds do not have their own lexical representations.

decomposed in order to be understood. The alternative use of compounds that are listed in a database would limit experimental control and may make the interpretation more difficult because listed compounds may have potentially interfering whole compound representations. As we are not aware of comparable research for the auditory domain, we chose compounds with no database entry as a starting point.

To manipulate the semantic integration difficulty for second (non-head) and third (head) constituents, we varied the semantic plausibility of the second and the third constituents independently. For all stimuli, the plausibility of the second constituent was varied given the first constituent; the plausibility of the third constituent was varied given the first two constituents. To construct the stimuli, different groups of participants were asked to generate a two-constituent compound in response to single nouns (used as the initial constituent), and, in turn, from these two-constituent compounds three-constituent compounds (see Method section). Based on this procedure, the compounds are assumed to have an AB-C structure where the initial two constituents (A+B) modify the head constituent (C). For example, “chicken leg dinner” is interpreted as a dinner where chicken legs are served (AB-C) as compared with “chicken wallpaper” which could be a wallpaper with chickens on it (A-BC).

As linguistic processes can be very rapid, we used the ERP technique for its high temporal resolution. Semantic processing in general has been associated with the N400, a negative ERP deflection that peaks around 400 ms after stimulus onset and has typically a centroparietal scalp distribution (Van Petten, & Luka, 2006; Kutas, & Federmeier, 2000 for reviews). Increased semantic processing (e.g. a word that is difficult to integrate semantically) results in an increased N400. This effect can begin as early as 200 ms after stimulus onset (Van Petten, Coulson, Rubin, Plante, & Parks, 1999).

Note that recently, also P600 effects (a posterior positivity peaking around 600 ms) which are often associated with syntactic/structural processing (Kaan, & Swaab, 2003;

Friederici, 2002; Hagoort, Brown, & Groothusen, 1993; Osterhout, & Holcomb, 1992) have been reported in response to semantic manipulations in sentence processing (Kolk, & Chwilla, 2007; Kolk, Chwilla, Van Herten, & Oor, 2003; Münte, Heinze, Matzke, Wieringa, & Johannes, 1998). For example, Kolk et al. (2003) presented syntactically well-formed sentences (e.g. ”The cat that fled from the mice ran through the room.”). When the sentences became semantically highly unlikely (here at ”mice”), a P600 effect was elicited. Subsequently the P600 was proposed to reflect a structural correction of the unexpected or implausible sentence due to difficulties with the grammatical-semantic constraints (e.g. thematic role assignment; for a discussion see Kolk, & Chwilla, 2007; Kuperberg, 2007). These findings suggest that late positivities can be associated with semantic manipulations.

Recently, Koester, Gunter, and Wagner (2007) proposed that the N400 component is sensitive to the lexical-semantic integration of compound constituents. In that study the processing of acoustically presented, low frequency semantically transparent (e.g. ”blackbird”) and opaque compounds (e.g. ”black mail”) was compared. In accordance with the notion that transparent but not opaque compounds can be understood by semantic constituent integration, an N400 effect was observed for transparent compared with opaque compounds during the presentation of the head constituents. This interpretation of the N400 to reflect specifically semantic integration as opposed to general cognitive costs of combination was lately confirmed by Bai, Bornkessel-Schlesewsky, Wang, Hung, Schlesewsky, & Burkhardt (2008). These authors investigated the semantic disambiguation within acoustically presented Chinese compounds.

The delayed account of compound constituent integration suggests that semantic integration does not begin before the head constituent is perceived. Specifically, the semantic plausibility manipulation of the second constituents should not lead to an N400 effect (or any other ERP effect) during the second constituents. The semantic plausibility manipulations of the second and the third constituents should lead to an N400 effect during the presentation of the head constituents. Since all constituents are integrated at more or less the same time, when the head constituent is detected, the effects of both plausibility manipulations should be additive and no interaction is expected. In contrast, the incremental account proposes that integration begins during the second constituent and that semantic plausibility of non-head and head constituents interact. Conceptual unification (we reserve this term for the integration of all constituents yielding the meaning of the whole compound; Inhoff et al., 2000) takes place when the head constituent becomes available. In particular, we expect an increased N400 for the less plausible second constituents during the presentation of the second and for less plausible head constituents during the presentation of the head constituents. In addition, if the result of integrating the initial two constituents is further modified during conceptual unification an interaction of both plausibility manipulations is expected.

Method

Participants

Thirty-two native speakers of German (16 female) participated for monetary compensation. On average they were 24;2 years old (range 19–30 yrs.), right-handed and gave written informed consent. All participants had normal or corrected-to-normal visual and auditory acuity.

Design

The experiment used a 2×2 within subjects-design. The experimental factors were semantic plausibility of the second (2) and the third (2) constituent. Each initial constituent was used to form 4 experimental stimuli; it was either followed by a plausible or a less plausible non-head constituent (by non-head constituent we will refer to the second constituent throughout). Each of these was then again followed by a plausible or less plausible head constituent. As a shorthand for the experimental conditions, we will use ”LL” (both constituents of low plausibility), ”LH” (non-head of low, head of higher plausibility), ”HL” (non-head of higher, head of low plausibility), and ”HH” (both constituents of higher plausibility). Note that before the presentation of the head constituent, the semantic plausibility manipulation of the head is not effective. The dependent variables are the ERP measure and the accuracy of the behavioural responses. Reaction times were not analysed due to the delayed judgement task (see Procedure).

Materials

Two-hundred mono-morphemic, nouns (monosyllabic & disyllabic) were selected to create the compounds for the four experimental conditions (LL, LH, HL, & HH; see above). In a first pre-test, these nouns were presented acoustically to 20 participants. Their task was to write down the first noun-noun compound that came to mind, i.e. they had to generate a head constituent for the given noun.[2] Participants were instructed that the heads had to be nouns.

The most often generated head constituents were selected for each initial constituent to form the plausible second non-head constituents. At this stage, stimuli were deleted from the item pool, if the most often generated head constituent resulted in an existing two-constituent compound according to the Celex database (Baayen et al., 1995). To obtain less plausible non-head constituents, nouns were selected that were not generated by any participant. These less plausible non-head constituents were matched on an item basis to the plausible non-head constituents regarding their frequency of use, number of syllables, duration, and stress pattern. In case participants changed the word form of the presented noun, e.g. if they included a linking element (”KalbSmaske” [calf$_{\text{animal}}$ mask] for KALB+MASKE), the same change was applied when creating less plausible non-head constituents.

The remaining two-constituent compounds were presented to a new group of 20 participants to create the third constituents, i.e. plausible and less plausible heads. The same

[2]Participants had to write down the whole compound to see whether they understood the given noun correctly.

procedure was used for presentation, determination of plausible constituents, and matching of less plausible constituents. The whole procedure resulted in a set of 56 three-constituent compounds per experimental condition as listed in the Appendix, Table A. In addition, 56 three-constituent compounds from the Celex database (Baayen et al., 1995) were included as filler items.

In order to check whether participants had constructed compound words and not provided merely associated words, the first pre-test was repeated with a different instruction. If participants simply wrote down nouns that came to mind upon hearing the initial constituent nouns, the same nouns should be generated under a word association instruction. When 20 participants generated the first noun that came to mind for the initial constituents of our stimuli, only 12.3 % of the responses were identical with our plausible second constituents. Therefore it is suggested that the compound stimuli do not reflect simple word associations.

A professional female speaker produced all stimuli for recording purpose with a natural prosody. The acoustic signal of each compound was visually inspected and acoustically tested to determine the onset of the non-head and head constituent. Recordings were only adapted for loudness. The four conditions did not differ significantly regarding their constituent length, lexical frequency, or fundamental frequency (using the analysis procedure described in Koester, Gunter, Wagner, & Friederici [2004] for fundamental frequency). For stimulus characteristics and the cloze probability values (Taylor, 1953)[3] of the plausible constituents see Table 1.

For the experimental task, two target words were selected for each compound. One target word was semantically related to the whole compound, the other was not related. This relatedness was tested in a further pre-test in which the compounds were presented

[3]Cloze probability values are usually interpreted in terms of expectancy. Constituent plausibility in the present study depends on the preceding constituent(s) as the expectancy of a specific word depends (partially) on the preceding context. Hence, cloze probability may serve as an estimate of constituent plausibility.

acoustically to another 10 participants. In this test, participants had to indicate which of the two target words was semantically related to the compound. For all experimental items, selection accuracy was greater than 80 %. Participants of the pre-tests did not take part in the following experiment.

Procedure

Participants were seated in a dimly lit, sound attenuated, and electrically shielded booth in front of a computer screen (distance 100 cm). Instructions were given to sit calm but comfortably and not to blink while a cross-hair was visible. Participants received a block of twelve trainings trials which were not used in the experiment. Two pseudo randomised lists were created with no more than two successive presentations of any experimental condition. The presentation side of the related word was counterbalanced which resulted in a total of four experimental lists one of which was randomly assigned to each subject. The experiment consisted of four blocks, and the whole session lasted about 45 min.

Each trial began with a cross-hair presentation for 1000 ms. Next the compound was presented via loudspeakers while the cross-hair remained on the screen. The cross-hair was replaced by two words 500 ms after compound offset for the semantic similarity judgement. To ensure that the compounds were processed on a semantic/conceptual level, participants decided via a push-button response which of the two visually presented words was semantically related to the compound.

Recordings

The Electroencephalogram (EEG) was recorded from 56 Ag/AgCl electrodes placed according to the extended 10–20 system as suggested by the American Electroencephalographic Society (1991). The EEG was high-pass filtered (DC–70 Hz) and sampled with 500 Hz. To control for eye movements bipolar horizontal and vertical electrooculograms (EOG) were recorded. Electrode impedance was kept below 5 kΩ and the left mastoid was used as reference.

Data analyses

Automatic rejection was used and visually double-checked to exclude all epochs in which (eye) movements or blinks occurred (EEG ± 25 µV; EOG ± 50 µV). Incorrectly answered trials (10.6 %) were also excluded from the analyses. In total, 12.6 % of the trials were excluded from the analyses. Ten regions of interest (ROI) were created that contained three electrodes each (from left to right, anterior 1–5: [AF7, F5, FC5], [AF3, F3, FC3], [AFZ, FZ, FCZ], [AF4, F4, FC4], [AF8, F6, FC6]; posterior 1–5: [CP5, P5, PO7], [CP3, P3, PO3] [CPZ, PZ, POZ], [CP4, P4, PO4], [CP6, P6, PO8]). Average ERPs were calculated separately for each ROI and for each constituent in the four experimental conditions. The ERPs were time-locked to the onset of the second and third constituent according to the respective experimental condition with a 200 ms baseline before constituent onset. Greenhouse-Geisser correction (Greenhouse, & Geisser, 1959) was applied where appropriate. In these cases, the uncorrected degrees of freedom, the corrected p values, and the correction factor epsilon are reported. ERPs were filtered (10 Hz low pass) for presentational purposes only.

Results

Participants evaluated the compounds with a high accuracy (overall 89.3 % correct). The mean values (standard deviations) of the four conditions are: LL 86.0 % (5.99), LH 89.6 % (4.03), HL 89.4 % (4.96), and HH 92.3 % (5.07). When subjecting the accuracy data to an ANOVA with the factors Semantic Plausibility (henceforth Plausibility) of the second and Plausibility of the third constituent, main effects of Plausibility of the second ($F(1,31) = 22.60$, $p < .0001$) and of the head constituent were obtained ($F(1,31) = 28.71$, $p < .0001$), but the interaction was not significant ($F(1,31) < 1$; ns). That is, judgement accuracy increased significantly for plausible constituents compared with less plausible constituents.

Figure 1 (upper panel) shows the ERPs time-locked to the onset of the second constituents. The plot shows an increased negativity for less plausible as compared to plausible second constituents peaking around 380 ms followed by a positivity starting after 500 ms. The mean amplitude values for all analysed time windows and conditions are given in Table 2. An ANOVA with the factors Plausibility of the second constituent (2), left–right (LR; 5), and anterior–posterior orientation (AP; 2) in the time window 300–500 ms yielded an interaction of Plausibility and LR ($F(4,124) = 6.21$; $p < .01$; $\varepsilon = 0.41$). Follow-up analyses for each ROI resulted in significant main effects of Plausibility in the central and left ROIs (AP1: $F(1,31) = 6.03$; $p < .05$; AP2: ($F(1,31) = 7.44$; $p < .05$; AP3: $F(1,31) = 5.38$; $p < .05$). No significant differences were observed in AP4 and AP5 (both Fs < 1; ns).

The negativity was followed by an increased positivity for less plausible second constituents. An ANOVA was performed with the factors Plausibility of the second constituent (2), LR (5), and AP (2) between 600 and 900 ms. There was a significant interaction of Plausibility with LR ($F(4,124) = 7.50$; $p < .01$; $\varepsilon = 0.50$) and with AP ($F(1,31) = 14.59$; $p < .001$). Subsequent ANOVAs performed separately for anterior and posterior ROIs yielded significant effects of Plausibility in the posterior ($F(1,31) = 14.23$; $p < .001$) but not in the anterior ROI ($F(1,31) < 1$; ns). The positivity was also significantly increased for less plausible second constituents in central and right ROIs (AP3: $F(1,31) = 6.80$; $p < .05$; AP4: $F(1,31) = 8.14$; $p < .01$; AP5: $F(1,31) = 7.33$; $p < .05$), but not in the left ROIs (AP1: $F(1,31) = 0.69$; ns; AP2: $F(1,31) = 2.81$; $p > .1$). The scalp distribution map of the Plausibility effect (difference between the less plausible and plausible condition) is shown in the lower panel of Figure 1.

As shown in Figures 2 and 3 (upper panel), the ERPs time-locked to the head constituents showed an increased negativity for less plausible as compared to plausible head constituents. However, the effect appears to be affected by the semantic plausibility of the second constituent. The effect of a less plausible head constituent was larger if preceded by less plausible second constituents than the effect of a less plausible head preceded by plausible second constituents (compare magnitude of negativies in Figs. 2 and 3). Since the negative going effect for head constituents was more extended in time than for second constituents, we used a broader time window (200–600 ms) for statistical analysis. The corresponding ANOVA with the factors Plausibility of the second (2), of the head constituent (2), LR (5), and AP (2) yielded main effects of Plausibility for both, the second ($F(1,31) = 30.42$; $p < .0001$) and the head constituent ($F(1,31) = 11.17$; $p < .01$) which are qualified by a three-way interaction of Plausibility of the second, the head constituent, and AP that was marginally significant ($F(1,31) = 3.46$; $p = .073$). Furthermore, Plausibility of the second constituent interacted significantly with AP ($F(1,31) = 22.08$; $p < .0001$) and with LR ($F(4,124) = 15.52$; $p < .0001$; $\varepsilon = 0.53$). Plausibility of the head constituent interacted also with AP ($F(1,31) = 4.46$; $p < .05$) and with LR ($F(4,124) = 6.9$; $p < .01$; $\varepsilon = 0.52$).

Subsequent ANOVAs determined the origin of the three-way interaction. At posterior sites, there was an interaction of Plausibility of the second and of the head constituent ($F(1,31) = 4.65$; $p < .05$) in addition to the main effects of Plausibility of the second ($F(1,31) = 76.04$; $p < .0001$) and of the head constituent ($F(1,31) = 16.57$; $p < .001$). In contrast, at anterior sites, there was a main effect of Plausibility of the second ($F(1,31) = 4.47$; $p < .05$), and of the head constituent ($F(1,31) = 5.18$; $p < .05$) but no interaction of these two factors ($F(1,31) < 1$; ns). The scalp distribution maps of the Plausibility effect (less plausible–plausible) are shown in the lower panel of Figures 2 and 3.

Taken together, less plausible second constituents elicited an increased negativity over central and left-hemispheric electrode sites between 300 and 500 ms that was followed by a positivity over parietal electrode sites (central-right) between 600 and 900 ms. The semantic plausibility of the head constituents elicited a broadly distributed negativity between 200 and

600 ms which interacted with semantic plausibility of the second constituent at posterior parts of the scalp. The effect was larger if the head constituents were preceded by less plausible, second constituents; the effect was smaller if they were preceded by plausible, second constituents.

Discussion

The present experiment investigated the time-course of lexical-semantic integration in auditory compound comprehension, by manipulating the integration difficulty of second (non-head) and head constituents. The main finding, an ERP modulation during the second constituents suggests that lexical-semantic integration is an incremental process.

The high accuracy in the semantic judgement task suggest that participants followed instructions. The higher accuracy for plausible compared to less plausible constituents additionally suggests that the manipulation of semantic plausibility effectively modulated the integration difficulty. Compounds with plausible constituents apparently led to an easier interpretation. Thus, it is suggested that participants processed the compounds on a semantic/conceptual level.

Regarding ERPs, less plausible non-head constituents elicited a biphasic ERP pattern, a central-left negativity (300–500 ms) and a posterior positivity (600 and 900 ms). The negativity is interpreted as an N400 effect (Bai et al., 2008; Koester et al., 2007; Hagoort Hald, Bastiaansen, & Petersson, 2004; Kutas, & Federmeier, 2000) whereas the positivity might be an instance of a P600 effect (Kolk, & Chwilla, 2007; Kuperberg, 2007). It is suggested that the N400 reflects the lexical-semantic integration difficulty of the initial and the second constituent. Although the N400 is also sensitive to processes associated with lexical access (Van Petten, & Luka, 2006; Deacon, Hewitt, Yang, & Nagata, 2000; Rugg, 1990), lexical access of constituents cannot explain the N400 effect. All compounds in the experiment were of lowest frequency and therefore have to be decomposed. Since plausible and less plausible constituents were closely matched to one another, lexical access can be assumed to be comparable in both conditions. Thus, it is highly unlikely that the N400 effect observed at the non-head position is due to processes associated with lexical access.

The delayed integration account led to the prediction that no ERP effect should be observed during the second constituents. In contrast, the incremental integration account predicts such an N400 effect as it was observed in the present study. Thus, the observed N400 effect argues against the delayed lexical-semantic integration as it is implied by the head-driven model of semantic compound processing (Isel et al., 2003) and rather supports the incremental integration account. The N400 effect is also in accordance with the suggestion of an immediate use of lexical(-semantic) information when it becomes available (DeLong et al., 2005; Van Berkum et al., 2005; Wicha et al., 2003) even though these studies investigated sentence processing. Furthermore, such an integration process implies that the constituents are separately activated, i.e. the compound has been decomposed semantically. The (implied) semantic decomposition of our stimuli is in accordance with and supports previous reports of semantic decomposition for transparent compounds in the auditory modality (Isel et al., 2003; Wagner, 2003; Pratarelli, 1995).

The N400 effect was followed by an increased positivity at posterior regions for less plausible non-head constituents compared too plausible ones. One possible explanation is that it reflects the online adaptation of the internal compound structure triggered by the perception of the head constituent. Auditory compound comprehension may start out from a two-constituent structure A-B where B is taken to be the head. If a third constituent is detected, this structure has to be changed, e.g. to AB-C. In any case, the function of constituent B has to be changed from head to modifier.

The larger positivity for less plausible non-head constituents may indicate that restructuring these compounds was more difficult compared to compounds with a plausible non-head constituent. Restructuring may have been more difficult because the integration of the initial two constituents consumed more cognitive resources as suggested by the N400 effect. We tentatively propose that the positivity is a P600 component. This interpretation is in agreement with findings from the sentence processing level which show that P600 effects can be elicited by semantic manipulations (Kolk, & Chwilla, 2007; Kuperberg, 2007, see above). More generally, the occurrence of a P600 suggests that the so far integrated constituents (A+B) are not discarded but re-analysed to yield an appropriate structural representation of the compound. Further research needs to confirm this interpretation.

Less plausible head constituents elicited an increased negativity (200–600 ms) after constituent onset with a centroparietal maximum. In line with the predictions, this negativity is interpreted as an N400 effect. This N400 effect is taken to reflect the lexical-semantic integration of all constituents into a unified concept (Bai et al., 2008; Koester et al., 2007; Hagoort et al., 2004; Kutas, & Federmeier, 2000). It is argued that processes associated with lexical access are unlikely to account for this N400 effect because plausible and less plausible head constituents were closely matched resulting in comparable processes of lexical access. Here, the N400 effect was not followed by a positivity or any other ERP effect. The absence of a positivity (P600) for the third constituents is in accordance with the interpretation that the positivity for non-head constituents reflects the adaptation of the compound structure. As the third constituents were the last constituents of our stimuli, no further adaptation of the compound structure was necessary and no positivity would be expected.

There was also a main effect of semantic plausibility of the second constituents in the ERP analysis of the head constituents. The ERPs were more positive if the preceding, second constituents were less plausible compared with preceding plausible constituents. Therefore, it is suggested that the main effect of second constituents during the head is a reflection of the P600 effect elicited by less plausible second constituents. Note that in line with this argument, the occurrence of the P600 effect overlapped temporally with the presentation of the head constituents.

Finally, there was also an interaction between the plausibility of the second and the head constituents at posterior parts of the scalp. That is, the N400 effect in response to the head constituents was larger when the preceding non-head constituents were less plausible compared with preceding plausible non-head constituents. This interaction suggests that the semantic relation between the initial and the second constituent influences the conceptual unification during the head constituents. Therefore, it is proposed that the representation of the integrated initial two constituents is not discarded when a further constituent is perceived. Rather, this initial integration seems to be taken into account during conceptual unification.

The present data do not support a special role of the head constituents for semantic integration processes in auditory compound comprehension beyond their mere necessity for conceptual unification as they provide the core meaning of (semantically transparent) compounds. Semantic integration seems to begin before the head constituent is perceived and, thus, seems not to depend on the availability of the head. As far as semantic integration includes access of constituent meaning, the present data suggest that, at least for German, semantic constituent accesss is incremental (Pratarelli, 1995) similar to morphosyntactic constituent access (Koester et al., 2004).

At any rate, some questions remain unanswered. The N400 effect for second constituents was distributed over central-left regions whereas the N400 for head constituents was characterised by a centroparietal maximum. During the integration of the initial two constituents, the detection of the head constituent could have elicited the restructuring of the compound. Such a temporal overlap of cognitive processes can affect the scalp distribution of the associated ERP components (Regan, 1989). Therefore, it is suggested that a partial temporal overlap of the cognitive processes reflected in the N400 and the P600 in response to second constituents is responsible for the central-left scalp distribution of the N400 effect.

It is worth noting that the N400 effect for the head constituents was larger in amplitude than for the second constituents although the cloze probability for plausible head constituents was lower than for second constituents (see Tab. 1). This observation contrasts with sentence processing where larger N400 effects are related to higher cloze probability values (relative to an unrelated condition; Kutas, & Hillyard, 1984). However, in sentences more words make it easier to predict a subsequent word. That is, more words will generally increase the cloze probability for subsequent words. The case is different for compounds. Here, the last constituent alone determines the semantic category of the compound. Therefore, more non-head constituents do not necessarily reveal more about the head constituent, i.e. they should not increase the cloze probability for head constituents. For example, even if all non-head constituents denote concrete entities, the head and therefore the whole compound can denote nevertheless an abstract entity (e.g. “bath towel rack offer”). In fact, the more constituents a compound has in German, the lower its frequency of use (Fleischer, & Barz, 1995). That is, two-constituent compounds are more common and may, thus, be more familiar than three- or four-constituent compounds. Hence, more non-head constituents may reduce the certainty with which a head constituent can be predicted as suggested by our cloze probability values. The present results suggest that the relation between the magnitude of the N400 effect and the cloze probability as it is known from sentence processing (Kutas, & Hillyard, 1984) does not necessarily hold for processes of word formation such as compounding. A relevant difference between sentences and compounds might be that the latter do not have a propositional content.

To our knowledge, this is the first investigation of lexical-semantic integration of acoustically presented three-constituent compounds. Only with such a design that uses compounds with at least three constituents, it is possible to disentangle head-related integration processes from non-head integration processes. The present stimuli are proposed to have an AB-C structure, and compounds in the language under investigation are almost exclusively right-headed. Further research should inquire the processing of compounds with A-BC structures which may help to further specify the functional significance of the observed P600 effect. Other areas where compound processing deserves more attention include languages with left-headed compounds (e.g. Italian or French; El Yagoubi, Chiarelli, Mondini, Perrone, Danieli, & Semenza, 2008; Nicoladis, & Krott, 2007), language production (Koester, & Schiller, 2008; Bien, Levelt, & Baayen, 2005; Roelofs, 1996) and the processing of constituent relations (Gagné, & Spalding, 2009; 2004).

In summary, the present investigation provides new insights into the time-course of lexical-semantic integration in compounding which is a frequently used mechanism of word formation. The present results support previous studies that propose a specific sensitivity of the N400 to semantic processing costs within compounds (Bai et al., 2008; Koester et al., 2007). In contrast to the delayed integration account, our results indicate that lexical-semantic integration in auditory comprehension is an incremental process that begins before the head constituent is detected. Further research is necessary to extend the present results to compounds with higher frequencies as well as to other morphological domains. And, what about twinkletoes? Only A. A. Milne knows.

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Tables

Table 1: Stimulus examples for each condition, mean duration (in ms), frequency of use (per million), and cloze probabilities per condition. C1, C2, C3–first, second, & third constituent; LL–less plausible second and third constituent; LH–less plausible second and plausible third constituent; HL–plausible second and less plausible third constituent; HH–plausible second and third constituent

Example	Duration (ms)				Frequency (per million)			Cloze prob.	
	C1	C2	C3	total	C1	C2	C3	C2	C3
HH									
Durstlöschergetränk	409	358	623	1390	42	204	227	.45	.19
(thirst quencher drink)									
HL									
Durstlöscherplakat	409	373	581	1363	42	204	270	.45	0
(thirst quencher poster)									
LH									
Durstbrunneneimer	409	367	602	1378	42	360	254	0	.18
(thirst well bucket)									
LL									
Durstbrunnenkette	409	380	585	1374	42	360	290	0	0
(thirst well chain)									

Table 2: Mean ERP amplitude values (in µV) for the analysed time windows time-locked to the non-head (C2) and the head constituent (C3).

	C2		C3
Condition	300-500 ms	600-900 ms	200-600 ms
LL	-5.2	-6.2	-2.5
LH			-1.1
HL	-4.7	-7.2	-3.7
HH			-2.9

Figures

Figure 1: The ERPs for plausible (solid lines) and less plausible non-head constituents (dashed lines) time-locked to the onset of the non-head, i.e. the second constituents (upper panel). The horizontal arrow in the diagram of electrode P4 indicates the average duration of the non-head constituents. Negativity is plotted upwards in this and all subsequent ERP plots. Lower panel: the scalp distribution of the ERP difference (less plausible – plausible) for non-head constituents.

Figure 2: The ERPs for plausible (LH; solid lines) and less plausible head constituents (LL; dashed lines) time-locked to the head, i.e. the third constituents that were preceded by less plausible second constituents (upper panel), and the scalp distribution of the ERP difference (less plausible – plausible; lower panel).

Figure 3: The ERPs for plausible (HH; solid lines) and less plausible head constituents (HL; dashed lines) that were preceded by plausible second constituents time-locked to the head constituents (upper panel), and the scalp distribution of the ERP difference (less plausible – plausible; lower panel).

Appendix

Table A: All stimulus words with their approximate translations for the four experimental conditions. For the abbreviations see the caption of Table 1. The constituent boundaries of the stimuli are indicated by hyphens for illustrative purposes only; according to German spelling all compounds are written as one word (e.g. “Alarmglockensignal,” alarm bell signal).

HH	
Stimulus word	*Approximate translation*
Alarm-glocken-signal	alarm bell signal
Balkon-pflanzen-topf	balcony plant pot
Ballon-fahrt-absturz	balloon ride crash
Bienen-wachs-kerze	bee wax candle
Bus-fahrer-uniform	bus driver uniform
Dachs-bau-eingang	badger set entry
Damm-bruch-katastrophe	causeway leakage catastrophe
Durst-löscher-getränk	thirst quencher drink
Fels-brocken-lawine	crag chunk avalanche
Futter-napf-inhalt	feed bowl content
Gift-spritzen-gabe	poison injection administration
Hammer-stiel-befestigung	hammer handle mounting
Helm-pflicht-verordnung	helmet obligation order
Hut-ablage-regal	hat rack shelf
Jacht-hafen-gebühr	yacht harbour toll
Jacken-taschen-loch	jacket pocket hole
Joghurt-becher-entsorgung	yoghourt cup disposal
Käfig-haltungs-verbot	cage breeding prohibition
Kalbs-leber-wurst	calf liver sausage
Kamin-feuer-anzünder	chimney fire lighter
Kissen-schlacht-spaß	pillow fight fun
Kompott-schüssel-set	compote dish set
Kraut-salat-schüssel	cabbage salad key

Kuss-mund-lippen	kiss mouth lips
Lachs-schinken-brot	salmon bacon bread
Leim-tuben-stöpsel	glue tube plug
Mais-feld-ernte	corn field harvest
Mücken-stich-salbe	mosquito bite salve
Ozon-loch-vergößerung	ozone hole extension
Paket-dienst-service	parcel [delivery] service
Parfüm-flakon-form	scent flask form
Pfand-flaschen-urkunde	deposit bottle certificate
Pfannen-gericht-rezept	pan dish recipe
Pfeil-spitzen-gift	arrow head poison
Plakat-werbungs-agentur	poster advertisement agency
Quark-speisen-zubereitung	curd food preparation
Reh-kitz-mutter	deer fawn mother
Sarg-deckel-verschluss	coffin lid lock
Sauna-gang-affäre	sauna session affair
Schädel-decken-knochen	skull cap bone
Schaufel-bagger-führer	shovel digger operator
Scheichs-palast-wache	sheik palace guard
Schinken-speck-stück	bacon speck piece
Schrauben-dreher-griff	screw driver handle
Sekt-glas-tablett	(sparkling wine) glass tray
Senf-gurken-glas	mustard gherkin jar
Sopran-stimmen-sängerin	soprano voice singer
Spray-dosen-kappe	spray tin cap
Stroh-ballen-stapel	straw bale pile
Tablett-träger-schulung	tray carrier instruction
Tassen-henkel-bruch	cup handle rupture
Teig-waren-gebäck	dough products pastry
Villen-gegend-bewohner	mansion area resident
Zimt-stangen-reibe	cinnamon stick grater
Zoo-besuchs-tag	zoo visit day
Zungen-piercing-stecker	tongue piercing stud

HL	
Stimulus word	*Approximate translation*
Alarm-glocken-konzert	alarm bell concert
Balkon-pflanzen-öl	balcony plant oil
Ballon-fahrt-wetter	balloon ride weather
Bienen-wachs-schaden	bee wax damage
Bus-fahrer-legende	bus driver legend
Dachs-bau-klima	badger set climate
Damm-bruch-barrikade	causeway leakage barricade
Durst-löscher-plakat	thirst quencher poster
Fels-brocken-besitzer	crag chunk owner
Futter-napf-rinne	feed bowl chute
Gift-spritzen-zimmer	poison injection room
Hammer-stiel-materie	hammer handle matter
Helm-pflicht-behörde	helmet obligation authority
Hut-ablage-schicht	hat rack layer
Jacht-hafen-major	yacht harbour major
Jacken-taschen-ring	jacket pocket ring
Joghurt-becher-monopol	yoghourt cup monopoly
Käfig-haltungs-konflikt	cage breeding conflict
Kalbs-leber-fass	calf liver barrel
Kamin-feuer-ursache	chimney fire cause
Kissen-schlacht-schrei	pillow fight howl
Kompott-schüssel-lärm	compote dish noise
Kraut-salat-schnecke	cabbage salad slug
Kuss-mund-wunder	kiss mouth wonder
Lachs-schinken-lust	salmon bacon desire
Leim-tuben-plastik	glue tube sculpture
Mais-feld-leiche	corn field corpse
Mücken-stich-blut	mosquito bite blood
Ozon-loch-anomalie	ozone hole abnormality
Paket-dienst-kunde	parcel service customer

Parfüm-flakon-dieb	scent flask thief
Pfand-flaschen-sparte	deposit bottle branch
Pfannen-gerichts-ursprung	pan dish origin
Pfeil-spitzen-fund	arrow head discovery
Plakat-werbungs-katalog	poster advertisement catalogue
Quark-speisen-gelatine	curd food gelatine
Reh-kitz-märchen	deer fawn myth
Sarg-deckel-motiv	coffin lid motif
Sauna-gang-tabelle	sauna session chart
Schädel-decken-zelle	skull cap cell
Schaufel-bagger-messe	shovel digger fair
Scheichs-palast-treppe	sheik palace staircase
Schinken-speck-fleisch	bacon speck meat
Schrauben-dreher-mord	screw driver murder
Sekt-glas-patent	sparkling-wine glass patent
Senf-gurken-rest	mustard gherkin rest
Sopran-stimmen-finale	soprano voice finale
Spray-dosen-beutel	spray tin bag
Stroh-ballen-scheune	straw bale barn
Tablett-träger-weste	tray carrier waistcoat
Tassen-henkel-schmutz	cup handle filth
Teig-waren-trichter	dough products funnel
Villen-gegend-adresse	mansion area address
Zimt-stangen-waffel	cinnamon stick waffle
Zoo-besuchs-zeit	zoo visit time
Zungen-piercing-hütte	tongue piercing cabin

LH

Stimulus word	*Approximate translation*
Alarm-karten-sicherung	alarm card safeguard
Balkon-reden-schreiber	balcony speech writer
Ballon-fee-geschichte	balloon fairy story
Bienen-volks-stamm	bee colony tribe

Bus-fenster-kurbel	bus window crank
Dachs-blick-richtung	badger glance direction
Damm-schutz-wall	causeway protection rampart
Durst-brunnen-eimer	thirst well bucket
Fels-inschrift-entdeckung	crag inscription discovery
Futter-gong-schlag	feed gong beat
Gift-drüsen-sekret	poison gland secretion
Hammer-sieges-feier	hammer victory party
Helm-pracht-feder	helmet pomp feather
Hut-abnahme-pflicht	hat removal obligation
Jacht-zimmer-einrichtung	yacht cabin furnishing
Jacken-hälften-stoff	jacket share cloth
Joghurt-müsli-frühstück	yoghourt cereal breakfast
Käfig-schaukel-stuhl	cage swing chair
Kalbs-masken-träger	calf mask wearer
Kamin-klappen-hebel	chimney shutter lever
Kissen-stroh-füllung	pillow straw filling
Kompott-keller-schlüssel	compote cellar key
Kraut-gewürz-mischung	cabbage spice blend
Kuss-druck-stelle	kiss impression mark
Lachs-flossen-suppe	salmon fin soup
Leim-flächen-maß	glue plane measure
Mais-bier-brauer	corn beer brewer
Mücken-flug-bahn	mosquito flight path
Ozon-stress-auswirkung	ozone stress effect
Paket-weg-verfolgung	parcel track trace
Parfüm-geschmacks-test	scent taste test
Pfand-schreiben-papier	deposit letter paper
Pfannen-karton-aufschrift	pan cardboard label
Pfeil-wunden-verband	arrow cut bandage
Plakat-pleite-geier	poster bankrupt vulture
Quark-sorten-auswahl	curd variety selection
Reh-pirsch-jagd	deer stalk hunt

Sarg-schreiner-lehrling	coffin carpenter apprentice
Sauna-plan-erstellung	sauna plan compilation
Schädel-beulen-schmerzen	skull bump pain
Schaufel-einsatz-kommando	shovel mission command
Scheichs-fabrik-angestellter	sheik factory employee
Schinken-witz-erzähler	bacon joke narrator
Schrauben-bolzen-material	screw bolt material
Sekt-bade-wanne	sparkling-wine bath tub
Senf-mühlen-körner	mustard mill grains
Sopran-noten-ständer	soprano note stand
Spray-lager-halle	spray stock hall
Stroh-stoppel-feld	straw stubble field
Tablett-essen-ausgabe	tray food counter
Tassen-vorrats-schrank	cup reserve cupboard
Teig-kugel-masse	dough ball mass
Villen-abriss-firma	mansion demolition company
Zimt-puder-dose	cinnamon powder container
Zoo-bericht-erstatter	zoo report correspondent
Zungen-pfeifen-ton	tongue whistle sound

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Stimulus word	*Approximate translation*
Alarm-karten-linie	alarm card line
Balkon-reden-beifall	balcony speech applause
Ballon-fee-verhalten	balloon fairy behaviour
Bienen-volks-feind	bee colony enemy
Bus-fenster-schramme	bus window mark
Dachs-blick-foto	badger glance picture
Damm-schutz-blei	causeway protection lead
Durst-brunnen-kette	thirst well chain
Fels-inschrift-romantik	crag inscription romance
Futter-gong-schliff	feed gong polish
Gift-drüsen-modell	poison gland model

Hammer-sieges-roman	hammer victory novel
Helm-pracht-kugel	helmet pomp ball
Hut-abnahme-knecht	hat removal menial
Jacht-zimmer-gegenstand	yacht cabin item
Jacken-hälften-keim	jacket share germ
Joghurt-müsli-menge	yoghourt cereal amount
Käfig-schaukel-lied	cage swing song
Kalbs-masken-nase	calf mask nose
Kamin-klappen-metall	chimney shutter metal
Kissen-stroh-milbe	pillow straw mite
Kompott-keller-mauer	compote cellar wall
Kraut-gewürz-dünger	cabbage spice fertiliser
Kuss-druck-faktor	kiss impression factor
Lachs-flossen-kante	salmon fin rim
Leim-flächen-wand	glue plane board
Mais-bier-kessel	corn beer tank
Mücken-flug-start	mosquito flight start
Ozon-stress-kontrolle	ozone stress check
Paket-weg-etappe	parcel track leg
Parfüm-geschmacks-streit	scent taste argument
Pfand-schreiben-autor	deposit letter author
Pfannen-karton-feuer	pan cardboard fire
Pfeil-wunden-gesicht	arrow cut face
Plakat-pleiten-phase	poster bankrupt phase
Quark-sorten-liste	curd variety list
Reh-pirsch-netz	deer stalk net
Sarg-schreiner-hammer	coffin carpenter hammer
Sauna-plan-aktion	sauna plan activity
Schädel-beulen-stein	skull bump stone
Schaufel-einsatz-prämie	shovel mission bonus
Scheichs-fabrik-ingenieur	sheik factory engineer
Schinken-witz-kapitel	bacon joke chapter
Schrauben-bolzen-kapazität	screw bolt capacity

Sekt-bade-schürze	sparkling-wine bath skirt
Senf-mühlen-werbung	mustard mill advertisement
Sopran-noten-bereich	soprano note domain
Spray-lager-termin	spray stock appointment
Stroh-stoppel-kurs	straw stubble course
Tablett-essen-portion	tray food share
Tassen-vorrats-preis	cup reserve price
Teig-kugel-kiste	dough ball box
Villen-abriss-meister	mansion demolition master
Zimt-puder-formel	cinnamon powder formula
Zoo-berichts-exemplar	zoo report copy
Zungen-pfeifen-tisch	tongue whistle table

Figure 1

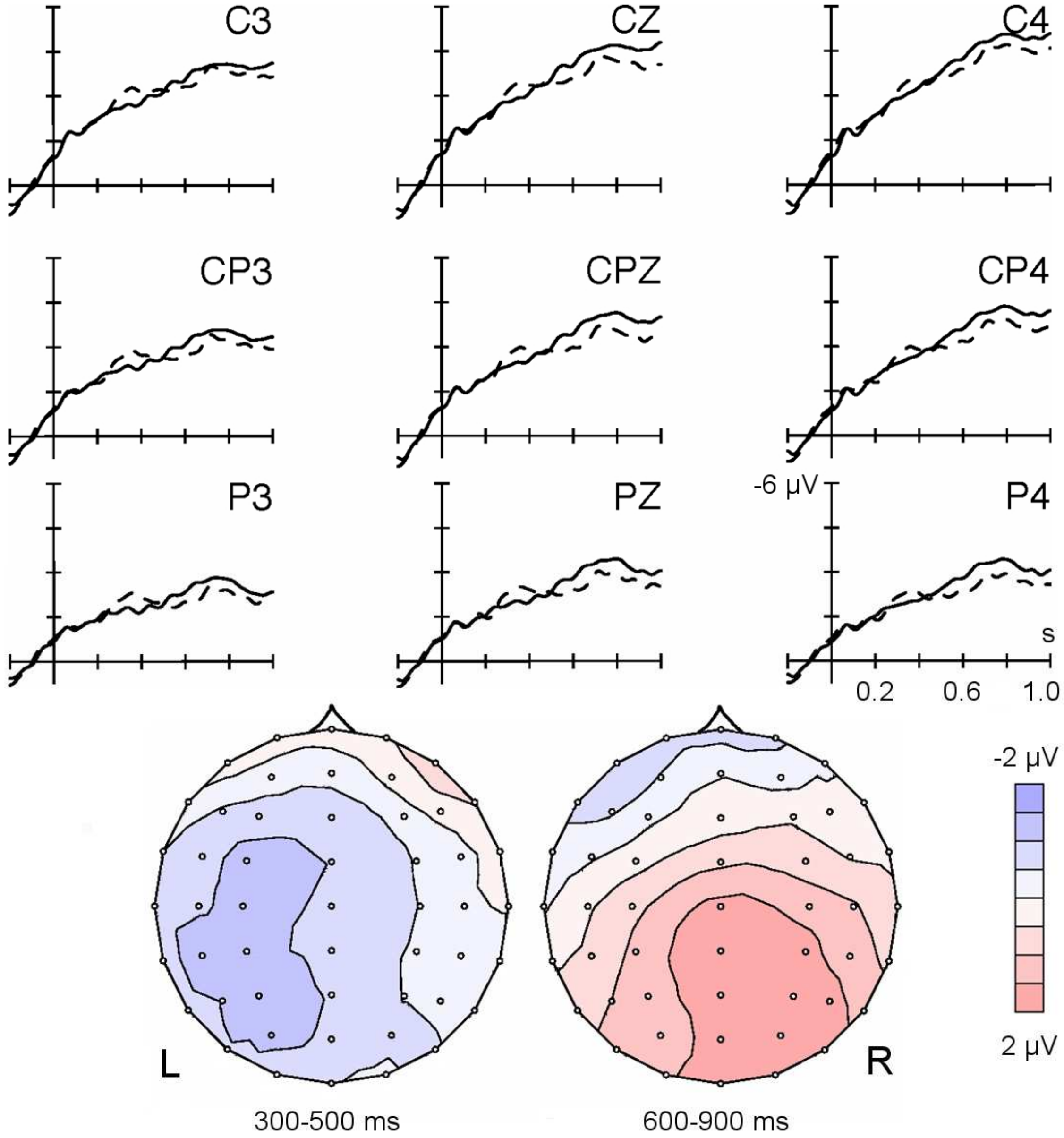
C3
CZ
C4
CP3
CPZ
CP4
-6 µV
P3
PZ
P4
s
0.2
0.6
1.0
-2 µV
2 µV
L
R
300-500 ms
600-900 ms

Figure 2

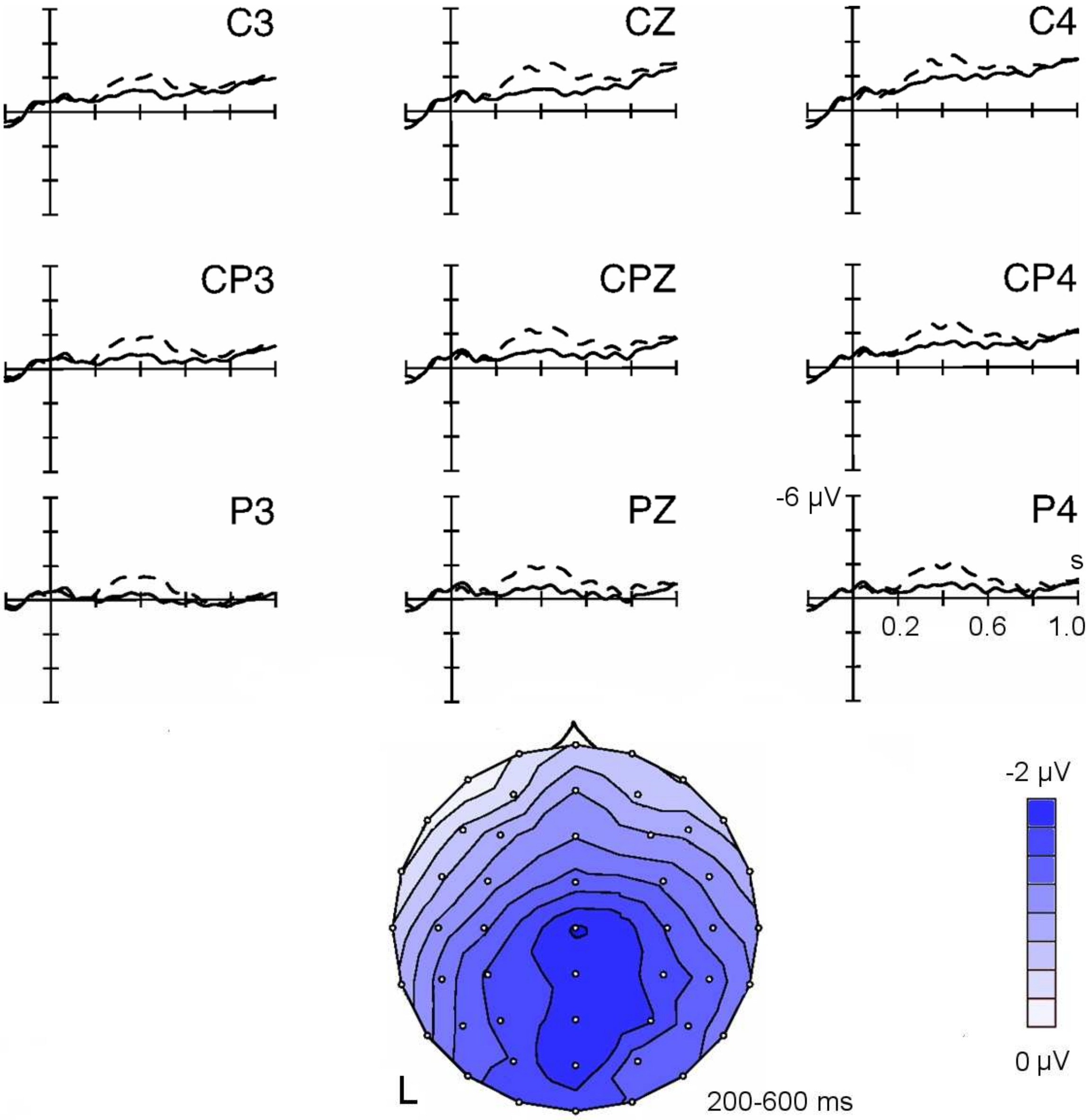

Figure 3