

The Electrophysiology of Language Production

Vitória Piai^{1,2}
Priscila Borges³

¹ Radboud University, Donders Centre for Cognition, Nijmegen, The Netherlands

² Radboudumc, Donders Centre for Medical Neuroscience, Department of Medical Psychology, Nijmegen, The Netherlands

³ University of Vienna, Vienna, Austria

1. Introduction

In the past decade, the well-established psycholinguistics tradition of using behavioral measures to study language production has been increasingly complemented with electrophysiological investigations. The electrophysiological signal has excellent temporal resolution, which is critical for understanding processes that unfold at the subsecond time scale. Here, we provide a selective review of single word production studies, focusing mostly on conceptually driven word production tasks performed by healthy adult speakers. We also provide pointers to the literature on speech-motor aspects of production, multi-word production and word production by speakers with brain damage. The reviewed topics include how the field has evolved over time, what kinds of questions researchers have tried to answer using electrophysiology, and what some of the challenges and future directions might be. The overview provided assumes background knowledge of the psycholinguistics of word production.

2. Electrophysiology

The electrophysiological signal measured over the scalp is thought to reflect post-synaptic potentials of thousands of synchronously activated neurons (Lopes da Silva, 2013). This activity generates a

complex pattern of signals varying in amplitude at different frequencies. Given that electricity travels nearly at the speed of light, what happens at the level of neurons is immediately recorded over the scalp, giving the electrophysiological signal excellent temporal resolution. However, given the effect of volume conduction, spatial resolution is poor and, in particular, underlying sources cannot be inferred from observations of a scalp topography alone. Magnetocencephalography (MEG) measures the magnetic field produced by the same electrical currents that are measured with the electroencephalogram (EEG), so for most psycholinguistic-research purposes, these two techniques (EEG and MEG) can be treated as very similar (for an overview and a discussion on the comparability between the two, see e.g., Lopes da Silva, 2013; Malmivuo, 2012). EEG signals can also be recorded intracranially, i.e., through invasive recordings (iEEG henceforth) in individuals requiring neurosurgery (for an overview applied to language research, see Flinker et al., 2018; Llorens et al., 2011). Since the signal is recorded from electrodes in direct contact with the brain, iEEG has excellent spatial resolution in addition to exquisite temporal resolution. Henceforth, we will use the term MEEG to refer to the electrophysiological signal in a way that is neutral to the specific recording technique.

Besides the technique for data acquisition (EEG, MEG, iEEG), there are also differences in the way the MEEG signal is processed. In the case of EEG event-related potentials (ERPs) or MEG event-related fields (ERFs), sometimes also termed local field potentials (LFPs) in the case of iEEG, the signal is not decomposed in the frequency domain. For scalp ERP/Fs, the signal is usually averaged over trials, whereas for LFPs, single-trial analyses are common, given the higher signal-to-noise ratio of iEEG data. By averaging the signal over trials, any amplitude modulation that is not consistent over trials is averaged out in the event-related response. Amplitude modulations that are not consistent over trials can originate from noise, in which case the ERP/Fs are the result of keeping brain responses consistently evoked by the stimulus. However, in certain cases, inter-trial inconsistent modulations originate from brain activity not phase-locked to a stimulus, in which case they would not be considered noise (see e.g., Mazaheri & Jensen, 2010; for a specific word-production demonstration, see Piai et al., 2014).

A different way of analyzing the MEEG signal consists of taking spectral information into account, yielding what is often termed “neural oscillations” in the literature. Oscillations are argued to enable a neuronal population to control the timing of neuronal firing, creating optimal windows for neuronal communication (e.g., Buzsaki & Draguhn, 2004). A power spectrum can be computed over a time window, thus disregarding the time course of power changes (e.g., Piai et al., 2015). Alternatively, a time-resolved power spectrum can be computed, providing a representation of how power changes for different frequencies over time (e.g., Piai, Roelofs, Jensen, et al., 2014). In both cases, both phase-locked and non-phase-locked brain activity is kept in the signal. A different approach,

microstate analysis, consists of characterizing the MEEG signal (either event-related responses or spectral information) in terms of changes in topographical configurations over time (e.g., Laganaro, 2014). Finally, for iEEG, it is common to analyze the signal focusing on a frequency range typically above 70 Hz (also called the high gamma range; “broadband” signal henceforth; e.g., Dufour et al., 2017). This broadband signal is known to correlate with single-neuron spiking (Manning et al., 2009).

Importantly, the most appropriate way of preprocessing the MEEG signal will depend on one's research question, with no particular method being superior to the others in an absolute sense (for examples of word production studies showing distinct effects between two approaches, see (Laaksonen et al., 2012; Piai et al., 2012; Piai, Roelofs, Jensen, et al., 2014). In the overview below, we discuss examples from the production literature using these different approaches.

3. Event-related responses

Early studies were interested in establishing the brain areas involved in speaking, particularly hemispheric lateralization effects occurring before speech, therefore not focusing on conceptually driven word production.

Focusing on the readiness potential, i.e., a slow rising negative-going potential linked to motor response preparation, preceding a speech task (i.e., saying words beginning with /p/ or /k/) and a non-speech task (i.e., spitting or coughing), McAdam and Whitaker (1971) found an enhanced negativity over left scalp locations prior to speech production but symmetrical potentials over left and right scalp locations before the nonspeech gestures. These results were presented as the first physiological evidence for left-hemisphere dominance in speech production in non-brain-

damaged participants. By contrast, Levy (1977) found larger readiness potential amplitudes over left scalp locations prior to the sequenced production of both speech and nonspeech movements but symmetrical readiness potentials over left and right sites when the movements were produced singly rather than in sequence. The results were taken to suggest that the hemispheric dominance effect was a function of task complexity rather than linguistic content. Expanding on these findings, Deecke et al. (1986) analyzed the averaged potentials elicited before the production of words beginning with /p/. To avoid respiration-related effects, participants were instructed to hold their breath prior to producing the words. Deecke et al. found an initial bilateral readiness potential that became stronger over left electrode sites in the final 100 ms preceding word onset. The results were interpreted as evidence that, while speech initiation involves both hemispheres, the left hemisphere dominates the execution of final speech motor operations.

Seeking clearer interpretations for the findings of lateralized motor control, Wohlert and Larson (1991) compared the ERPs preceding a lip protrusion task with those preceding a right-finger extension task performed by the same participants. The results showed that slow negative potentials became larger over left electrode sites before finger movements but remained even over right and left sites before lip movements. The authors concluded that the control of basic oral movements is unlikely to be dominated by the left hemisphere, but that left-hemispheric dominance could be involved in the motor control of more complex speech movements (see also Wohlert, 1993).

By focusing on motor speech, these earlier studies also highlight how speech preparation per se modulates the MEEG signal and, as such, how this phenomenon needs careful consideration when

interpreting effects in terms of cognitive factors, a point to which we return later (see e.g., for a critique, Piai, Riès, et al., 2015).

In a seminal study, Van Turennout and colleagues (1997) used ERPs to investigate the time course of semantic and phonological processes in word production. In the context of a two-choice reaction go/no-go paradigm, participants performed a categorization task before naming pictures. In the categorization task, participants determined the hand of their response based on semantic information (i.e., animacy of picture referents; e.g., picture: BEAR, “animate” – right-hand button), and the execution of their response based on phonological information (e.g., words ending in /r/ cued a go response, words ending in /n/ cued a no-go response; BEAR is a go response). Given the assumption made by models of language production that semantic information becomes available before phonological information during naming (e.g., Levelt et al., 1999), the authors expected that hand response preparation could start before the phonological information cued participants on whether or not to respond. In turn, this preparation would be reflected on the lateralized readiness potential (LRP), the onset of which would indicate when different types of information are used for response preparation. Specifically, the authors expected an LRP to appear on both go and no-go trials when the response hand was cued by semantic properties (i.e., animacy) and naming execution by phonological information (i.e., end phoneme). By contrast, in the reversed case, when phoneme decisions cued the response hand and semantic information cued naming execution, an LRP was expected only for go trials. Another prediction was that the LRP appearing for no-go trials would be insensitive to the location of the phonological information cueing response execution (i.e., word-

initial or word-final). The results of the experiments confirmed all of these predictions. The findings were interpreted as evidence that semantic activation precedes phonological encoding during naming, and that the onset of a word is encoded before its end. Moreover, the study propelled the combination of LRP with a go/no-go paradigm as a way to investigate the timing of semantic activation and phonological encoding in word production (see also van Turennout et al., 1999).

However, it was soon evident that this approach had limitations. Firstly, the LRP might not be a reliable index of the exact moment at which a given type of linguistic information is processed (Laganaro & Perret, 2011). Secondly, the task required participants to carry out cognitive operations other than those involved in the preparation of a verbal response, making it difficult to exclusively link the EEG patterns to production processes (Perret & Laganaro, 2013). Thus, ERP studies on word production later began to use delayed production paradigms as a way to more closely approximate real-world production scenarios while still avoiding motor-preparation effects and artifacts in the signal. In these paradigms, participants prepare their response but produce it only after some delay period, which makes effects/artifacts related to motor execution fall outside the analyzed window. For example, Jescheniak and colleagues (2002) showed how a delayed picture-naming task associated with a priming procedure could be used to study the activation of semantic and phonological information during word planning. Participants named pictures upon seeing a response cue that appeared after a delay period. During this period, words holding different relations to the picture name were presented auditorily. The authors found that the ERPs were less negative-going when participants heard prime words that were

phonologically or semantically related to the to-be-named object compared to unrelated controls. Additionally, they found that the phonological effect was absent when participants performed a nonlinguistic task involving judgment of object size. The results were considered evidence that semantic information does not automatically lead to activation of phonological information, thus being incompatible with models that allow for unconstrained cascading of activation from semantic to phonological representations (see for recent discussions e.g., Strijkers et al., 2017). Beyond its theoretical implications at the time, the study extended the LRP approach used in language production studies thus far to allow for investigating the types of code that are automatically activated during naming, leaving behind the need to rely on tasks requiring explicit and conscious extraction of semantic and phonological information. Nonetheless, this approach is also limited, as delaying naming might lead to alterations in the time course of the processes involved in speech production as well as to incomplete implementation of later processes such as phonological encoding and phonetic encoding (Laganaro & Perret, 2011).

Based on demonstrations that ERPs could be analyzed preceding overt naming, Costa and colleagues (2009) investigated the time course of lexical selection. Specifically, by manipulating the position of pictures belonging to the same semantic categories in a series of pictures named overtly (the cumulative semantic interference effect, Howard et al., 2006), Costa and collaborators attempted to identify when lexical selection takes place during production. Their results, depicted in Figure 1, showed significant correlations between the ordinal position of pictures, naming latencies, and

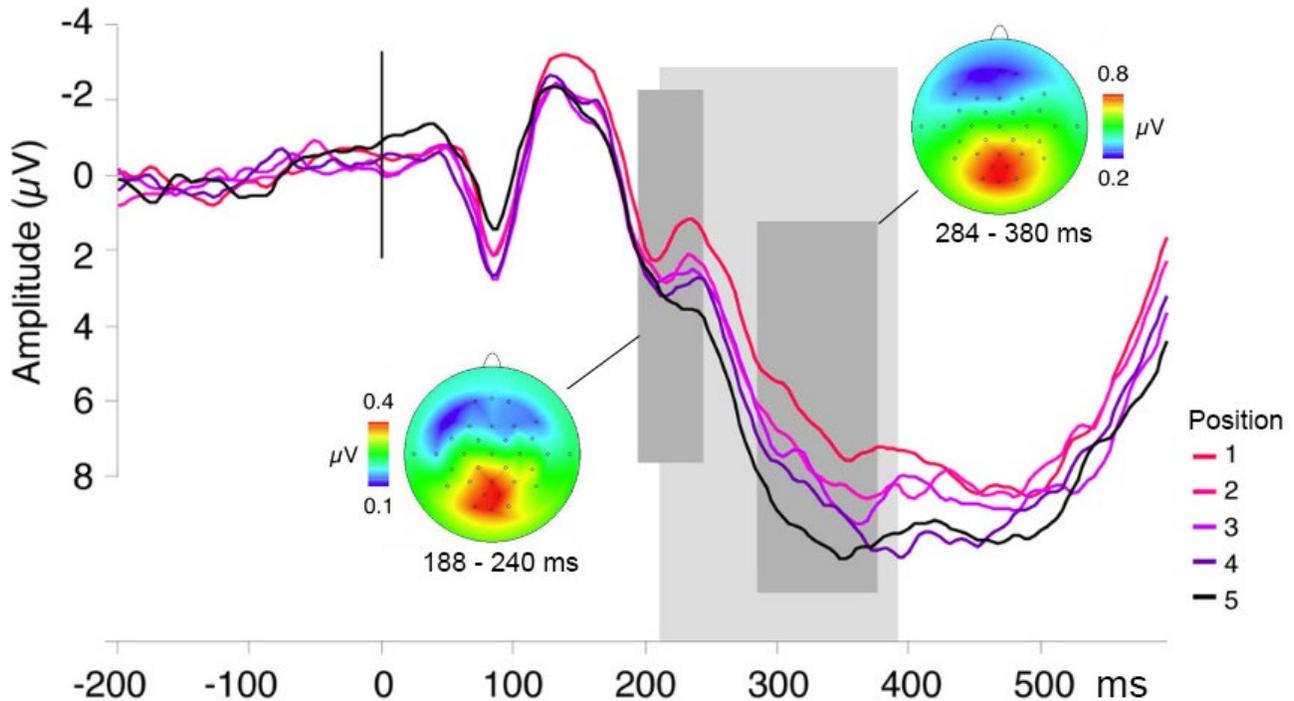


Figure 1. Event-related potentials in a continuous picture naming task corresponding to the five ordinal positions within semantic categories, time-locked to picture onset. The waveforms originate from ten posterior scalp electrodes. A cumulative increase in signal amplitude over ordinal positions is observed during the time period indicated by the light shaded area. Scalp topographies are shown for the averaged difference waves (the ERP for each position subtracted from its subsequent position), averaged over the two time windows indicated (dark shaded areas). Figure modified from courtesy of Kristof Strijkers.

ERP mean amplitudes starting around 200 ms post-picture onset and lasting 180 ms. The onset of these correlations was taken as evidence that lexical selection happens around 200 ms after picture presentation.

Also focusing on lexical selection, Aristei and colleagues (2011) investigated the time course of semantic interference and facilitation effects by comparing ERPs in a task that combined picture-word interference and semantic blocking. In this task, participants overtly named pictures presented in either categorically homogeneous, associatively homogeneous or heterogeneous blocks after hearing distractors that were either categorically related, associatively related or unrelated to the pictures. The manipulations of both types of

semantic context (distractor word and block) produced temporally overlapping ERP modulations around 200-250 ms post-picture onset, in addition to an overall interaction of distractor and blocking effects on ERPs around the same time. These findings were interpreted as indicating that facilitative and interfering semantic context effects originate from processing stages that are closely connected and that interact relatively early during word planning, being compatible with lexical competition models (e.g., Levelt et al., 1999). For a review of semantic context effects in word production, we refer the reader to Anders et al. (2019) and de Zubicaray and Piai (2019). For a discussion on the theoretical limitations of picture-

word interference and semantic context effects studies, see (Nozari & Pinet, 2020).

In line with Costa et al. (2009), other studies have found that a positive deviation around 200 ms after stimulus onset (termed the P2 component) might be an electrophysiological marker of lexical selection (Aristei et al., 2011; Fargier & Laganaro, 2020; Rabovsky et al., 2021; Rose et al., 2019; Strijkers et al., 2010). Rabovsky and colleagues (2021) compared ERP amplitudes related to naming objects with different levels of semantic richness and intercorrelational semantic feature density. Naming performance was better for semantically richer objects (i.e., objects whose names had many associated semantic features) and worse for objects whose features were more intercorrelated. In the ERPs, concepts with many semantic features and concepts with high feature density induced more positive amplitudes in posterior electrode sites between 200-550 ms post-picture onset. In addition, more positive amplitudes at these posterior regions correlated with slower naming times between 230 and 380 ms. This correlation was taken as evidence that the posterior positivity reflected the difficulty of lexical selection. In sum, several ERP studies on the time course of word-production stages support the idea that the P2 component might be a marker of lexical selection.

Whereas most EEG-ERP studies do not provide information on the neuronal generators of the brain responses, many MEG studies on picture naming do. Salmelin and colleagues (1994) reported the first MEG study on picture naming including source localization of ERFs. The authors showed that, upon seeing a picture, visual areas show increased activity first, followed by temporo-parietal-occipital junctions bilaterally between around 200-400 ms. Around 500 ms post-picture onset, activity in bilateral ventral premotor cortex

and inferior frontal gyrus was increased. Other studies from Salmelin and colleagues have provided further evidence on the neuronal generators of temporally circumscribed responses associated with word production. For example, Sörös and colleagues (2003) analyzed MEG data recorded while healthy participants named drawings using either a verb or a noun. The pattern of activity, which did not differ between the two types of naming tasks, followed bilaterally from occipital cortices in the first 200 ms post-picture onset, to bilateral posterior temporoparietal regions around 200-400 ms, and was left-lateralized in sensorimotor and occipital cortices around 400-800 ms post-picture onset (see also e.g., Liljeström et al., 2009; Vihla et al., 2006). In addition, the study reports behavioral and MEG data of one individual with left-hemisphere damage who presented with anomia that was particularly severe for nouns. In contrast to non-brain-damaged participants, the sources of cortical activity identified in this individual were different for nouns and verbs: Responses in the left middle temporal lobe were found only in object naming, and the latter was also linked to earlier and stronger activity in left inferior frontal gyrus (LIFG) relative to the action naming task. For studies focusing on individuals with aphasia following brain damage, see e.g., Laganaro et al. (2008, 2009).

The extent to which the spatio-temporal patterns of activity during picture naming are replicable is an important issue, as it has direct bearing on the interpretation of patterns that deviate from this “default”. A recent study examined the test–retest reliability of brain activity in a delayed picture naming task relative to a visual task (i.e., participants said ‘yes’ if a target picture was presented) performed over two different sessions (Ala-Salomäki et al., 2021). The results are shown in Figure 2. From 200 ms onwards, activity

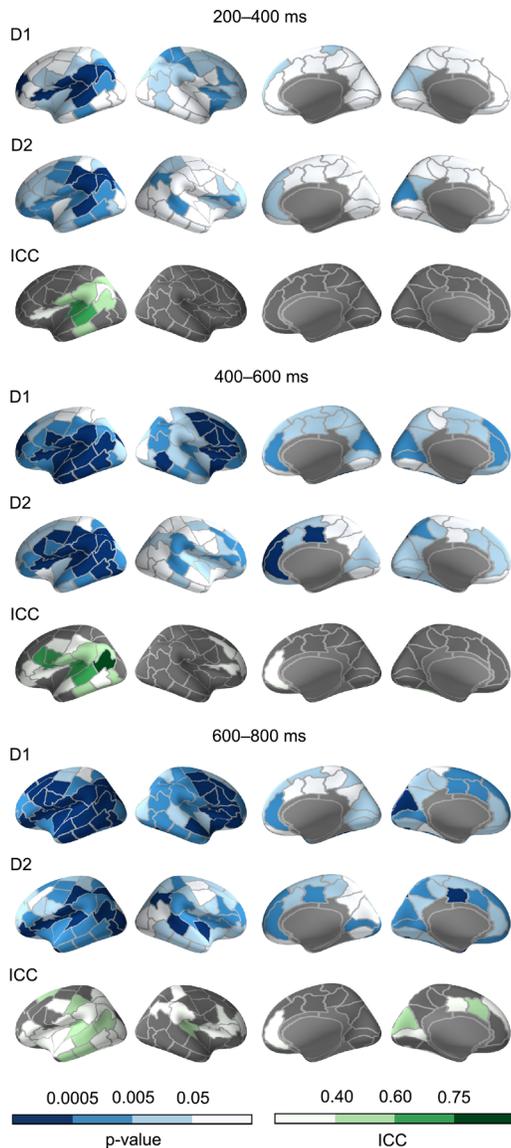


Figure 2. Source localization of the activity during delayed picture naming relative to the visual task for three different time windows relative to picture onset, as indicated on top of each panel/triplet. For session 1 (D1) and session 2 (D2), the blue colors indicate p-value thresholds. For the consistency of significant effects across the two sessions (ICC), the green colors indicate the intraclass correlation coefficients. The grey parcels were not used for the across-session consistency analysis. Reprinted from Ala-Salomäki, H., Kujala, J., Liljeström, M., & Salmelin, R. (2021). Picture naming yields highly consistent cortical activation patterns: Test-retest reliability of magnetoencephalography recordings. *NeuroImage*, 227, 117651.

increased in perisylvian language regions, including the middle temporal cortex and frontal cortex from 400 ms onwards, on both measurement days (rows D1 and D2 in Figure 2). Consistent activity across the two sessions (ICC rows in Figure 2) was detected in various left-hemisphere regions, namely sensorimotor (200–800 ms), parietal (200–600 ms), temporal (200–800 ms), frontal (400–800 ms), occipital (400–800 ms) and cingulate (600–800 ms). Additionally, consistent activity was found in the right superior temporal region (600–800 ms). Notably, the consistent pattern of spatiotemporal activity that emerged for delayed picture naming was in line with the proposed set of cortical areas typically associated with language production (e.g., Indefrey & Levelt, 2004). For a demonstration of variability and consistency of EEG microstates in word production, see Laganaro (2017; see also Laganaro et al., 2012, for a comparison between fast and slow speakers using EEG microstates analyses). Importantly, both studies underscore the relevance of evaluating group-level and individual-level consistency in studies of language production.

For reviews on ERPs/ERFs in word production, we refer the reader to Ganushchak et al. (2011), Munding et al. (2016), Perret and Laganaro (2013), Salmelin (2007), and Strijkers and Costa (2016).

3.1. Multi-word production

Following a common criticism to single-word production studies that this is hardly how we speak, researchers have also investigated noun-phrase production (e.g., saying “the brown cat”) and multi-word utterances. Bürki and Laganaro (2014) found that the production of “cat” corresponded to a shorter window of stable topography than the production of “the cat” or “the big cat” around 190–300 ms. This time window is in agreement with

estimates of the timing of grammatical encoding processes (Indefrey & Levelt, 2004). Additionally, from around 530 ms post-picture onset, a stable topographical pattern was longer for the production of “the big cat” relative to the other two types of utterances. The authors interpreted this difference as corresponding to the longer duration of phonological encoding for utterances with additional syllables and words. For additional multi-word production studies, see Eulitz et al. (2000), Pylkkänen et al. (2014) and Sikora et al. (2016).

Recently, Ries and colleagues (2021) extracted ERP components time-locked to the vocal onset of individual words presented in the context of multi-word utterances. Using a paradigm that required participants to recite four-word tongue twisters from memory at a regular pace, the authors were able to isolate two ERP components related to speech monitoring and word planning mechanisms, namely the error-related negativity and a late left anterior negativity, respectively. Although not tapping into conceptually driven production processes, this paradigm opens the door for future studies to investigate relevant operations involved in sequential word production such as phonological encoding and articulation.

4. Oscillatory responses

It is well known that during (finger or limb) movement preparation and execution, power between 15-30 Hz decreases (often termed “suppression”) over motor-related regions (Pfurtscheller & Lopes da Silva, 1999), subsequently increasing after movement execution (often termed “rebound”). This “suppression” in fact reflects the active involvement of brain regions. Among the first studies to investigate the oscillations underlying speech-motor activity was Salmelin and colleagues (1995). By comparing

participants moving their toes, fingers, or mouth, the authors showed that the 20-Hz rhythm is modulated by movement, but in a “motorotopic” manner (i.e., modulation over the hand area when moving the fingers, but over the face area when moving the mouth). In a later study (Salmelin & Sams, 2002), 20-Hz suppression and rebound over the motor face area in motor cortex was examined for both oral non-verbal tasks (e.g., making a kissing movement) and verbal tasks (e.g., silently articulating a vowel). The results showed that, for verbal tasks, the timing of the 20-Hz suppression was correlated between left and right mouth areas, whereas the rebound was left-lateralized. Moreover, the 20-Hz suppression was also present over the hand areas in the non-verbal tasks. Thus, as the linguistic content of lip and tongue movements increased, modulations of the 20-Hz rhythm became more focal or even left-lateralized.

The MEG study by Salmelin and colleagues (1994) was amongst the first to examine frequency-specific activity during picture naming. Activity in the 9-13 Hz range was suppressed during picture naming, starting from the occipital lobe, followed by bilateral frontal areas, and finally bilateral motor cortex. This suppression was strongest and lasted longer for overt naming versus covert naming and passively viewing pictures. Besides picture naming, oscillations in conceptually driven production have often been studied with verb generation using MEG. In this task, a verb is produced in response to a noun (e.g., “nightingale”, response: *sings*). Power decreases in the 15-30 Hz range are commonly observed, with sources being often found in the language dominant hemisphere, particularly in inferior and middle frontal gyri, and temporal and inferior parietal regions (Findlay et al., 2012; Fisher et al., 2008; Pavlova et al., 2019; see also Youssofzadeh et al., 2020 for a demonstration using visual and auditory naming).

Following-up on these findings, Pavlova et al. (2019) used MEG to investigate whether these oscillations are sensitive to semantic retrieval demands. Materials were such that a presented noun was either strongly associated with a single verb (e.g., “nightingale”, response: *sings*, less demanding) or weakly associated with multiple verbs (e.g., “paper”, many responses, more demanding). Power decreases in the 15-30 Hz range were found to be stronger for more demanding responses, an effect that was visible 700-500 ms before speech onset and that was localized to medial aspects of the frontal lobe bilaterally. The time window of this effect is consistent with the proposed timing of retrieval stages, prior to articulatory planning (Indefrey & Levelt, 2004).

Power decreases in the 10-30 Hz range are also typically found in association with conceptual and lexical retrieval. To study the initial stages of word production in a manner that tries to approximate real-life word production, Piai and collaborators have employed a context-driven word production task in which to-be-named pictures are presented following sentences with differing amounts of constraint (e.g., “the farmer milked a” versus “the child drew a” preceding the picture of a cow), see Figure 3A. During the pre-picture interval (red box in Figure 3A), conceptual and lexical retrieval are initiated following constrained sentences. Thus, the contrast between constrained and unconstrained sentences in this window provides a measure of the speaker’s internally driven conceptual and lexical preparation. A series of studies has shown that power is decreased in the 10-25 Hz range in the pre-picture interval following constrained relative to unconstrained sentences (Gastaldon et al., 2020; Klaus et al., 2020; Piai et al., 2017, 2018, 2020; Piai, Roelofs, & Maris, 2014; Piai, Roelofs,

Rommers, & Maris, 2015). These power decreases have been most consistently localized to the left inferior parietal lobule and left temporal lobe (mostly posterior), as shown in Figure 3B. The across-session consistency of this pattern in these left posterior brain regions was further established in an MEG study using the same task with two sessions spaced 2-4 weeks apart (Roos & Piai, 2020, Figure 3B). As previously mentioned, the consistency of this pattern is important for interpreting deviations from it following perturbation with non-invasive brain stimulation (Klaus et al., 2020, Figure 3C) and in individuals with brain damage (Piai et al., 2017, 2018; Figure 3D).

The study on the test–retest reliability of delayed picture-naming mentioned above also examined oscillations (Ala-Salomäki et al., 2021). From 400 ms post-picture onset onwards, power decreases were consistent in bilateral occipital, occipitotemporal, and parietal areas in the ranges of 4–7 Hz, 8–13 Hz, and 14–20 Hz. Power was also consistently decreased in the 14–20 Hz and 21–30 Hz ranges over motor regions in the time window of 800–1200 ms post-picture onset (see also Laaksonen et al., 2012).

A number of studies have examined oscillatory effects associated with picture-word interference, a demanding picture-naming task where participants have to ignore a superimposed distractor word. Using MEG, Piai, Roelofs, Jensen, and colleagues (2014) analyzed oscillatory activity associated with picture naming with semantically related (most demanding condition), semantically unrelated, and congruent (least demanding condition) distractors. The results are shown in Figure 4. Increases in 4-8 Hz activity between 350–650 ms were found for related compared to unrelated distractors and for related compared to congruent distractors. The generators of this effect

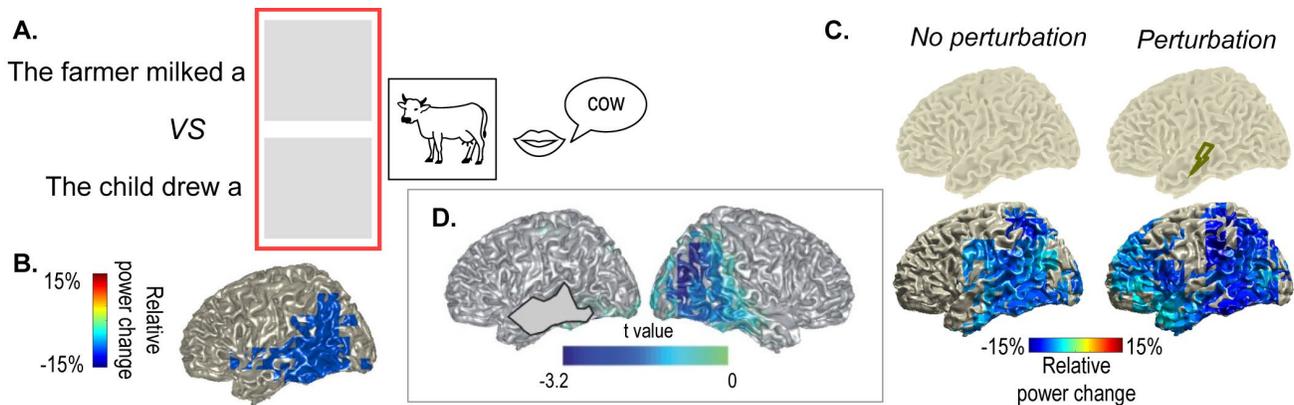


Figure 3. **A.** Context-driven picture naming with a constrained (upper) and unconstrained (lower) context. The pre-picture interval is marked by the red box. **B.** Source localization of the across-session consistent relative power changes in the 10-20 Hz range for constrained vs unconstrained contexts during the pre-picture interval (Roos & Piai, 2020). **C.** Source localization of relative power changes as in B following no perturbation (left) and perturbation (right) of the left middle temporal gyrus (through continuous theta burst stimulation, Klaus et al., 2020). **D.** Source localization of the context effect as in B and C (expressed as t values) for one individual with a stroke lesion in the left temporal lobe (in grey, Piai et al., 2017).

were found in superior frontal gyrus, possibly including the anterior cingulate cortex. This effect was interpreted to reflect the attentional control required to select the picture name under distracting conditions. Similar results were obtained by Shitova et al. (2017) and Krott et al. (2019) using EEG, even though a different pre-processing approach was taken to account for speech-related artefacts in each one of these studies (see also Piai & Zheng, 2019, for similar effects in language switching).

In summary, power decreases in the 10-30 Hz range are commonly found in tasks requiring conceptually driven word production. The generators of this effect are found not only in sensorimotor areas, in line with a motor speech role, but also in temporal and inferior parietal areas, which are commonly implicated in conceptual, lexical, and phonological aspects of word production (Indefrey & Levelt, 2004). There is also tentative evidence that power increases in the 4-8 Hz range, possibly originating from frontal areas

commonly associated with cognitive control, underlie the regulatory processes involved in speaking (Roelofs & Piai, 2011), but this phenomenon is less understood than the pattern of power decreases in the 10-30 Hz range.

For more studies on response and sentence planning, the reader is referred to Bögels et al. (2015), Jongman et al. (2020), Piai, Roelofs, Rommers, Dahlslett, et al. (2015), and Sauppe et al. (2021). For a more detailed review and discussion of oscillatory activity in word production, see Piai and Zheng (2019).

5. Intracranial EEG

Crone and collaborators (2001) provided one of the first illustrations of the broadband signal during word production tasks (i.e., picture naming, auditory word repetition, and word reading). Contrasting different input (visual vs. auditory) and output (signed vs. spoken) modalities, the authors found early broadband responses over the superior temporal gyrus (STG) for word repetition, and over

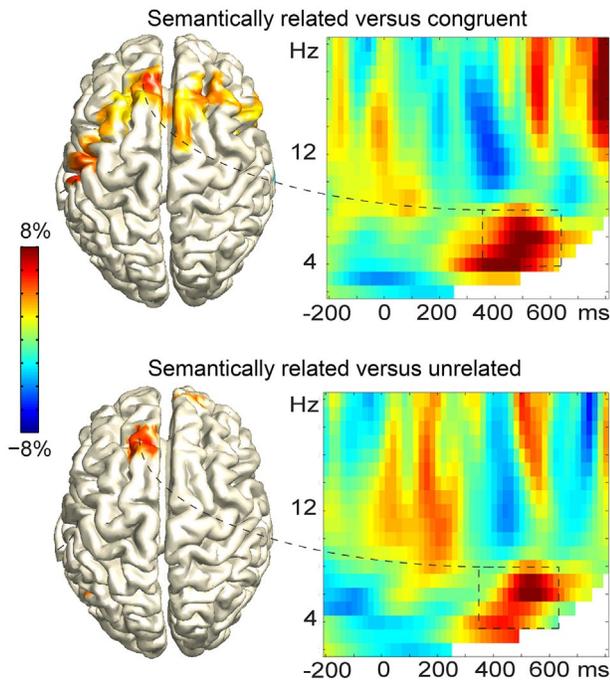


Figure 4. Spectro-temporal profile of the relative power differences originating from the superior frontal gyrus for the contrasts semantically related versus congruent distractors (upper) and semantically related versus unrelated distractors (lower) during picture naming. Modified from Piai, V., Roelofs, A., Jensen, O., Schoffelen, J.-M., & Bonnefond, M. (2014). Distinct patterns of brain activity characterise lexical activation and competition in spoken word production. *PloS One*, 9(2), e88674.

temporal-occipital cortex for picture naming and word reading. They also found late broadband responses over the tongue area of sensorimotor cortex for spoken responses and over hand areas for signed responses, with latencies varying according to the participant's behavioral response latencies across tasks.

Since this pioneering study, several iEEG studies have used the broadband signal to track language production processes. For example, employing a picture naming task, Edwards et al. (2010) found that activity related to motor-speech production began ~300 ms before verbal responses in peri-Rolandic cortices (pre- and postcentral

gyri), peaking around 100–200 ms after response onset (Figure 5; see Edwards et al. for results on verb generation). Interestingly, one electrode in the posterior middle temporal gyrus (light blue in Figure 5) showed increased activity starting around 300 ms post-picture onset, which remained sustained until about 200 ms before response, in line with the proposed time course of planning processes preceding articulation (Indefrey & Levelt, 2004). By contrast, electrodes over posterior STG (the two dark blue dots and lines in Figure 5) showed no increased activity during the same period.

An important question about the cognitive architecture of the language-production system relates to whether processes unfold serially or in parallel. Using the iEEG broadband signal, Dubarry et al. (2017) addressed this issue with a picture naming task and the analysis of significant activity concurrent between regions at the single-trial level. Figure 6 shows the results of these analyses. The data averaged over trials showed temporal overlap in the activity time courses between various regions, which would be interpreted as parallel processing. Critically, the single-trial analysis revealed a different pattern. The temporal overlap of activity between regions was relatively high for sensory cortices (e.g., striate cortex, transverse temporal gyrus, pink and purple colors in Figure 6), but substantially low in other regions (blue colors), including regions previously associated with aspects of conceptually driven word production. These results were interpreted to indicate that there are limits to the amount of parallel processing involved across word production stages (see also Munding et al., 2016, and subsequent commentaries).

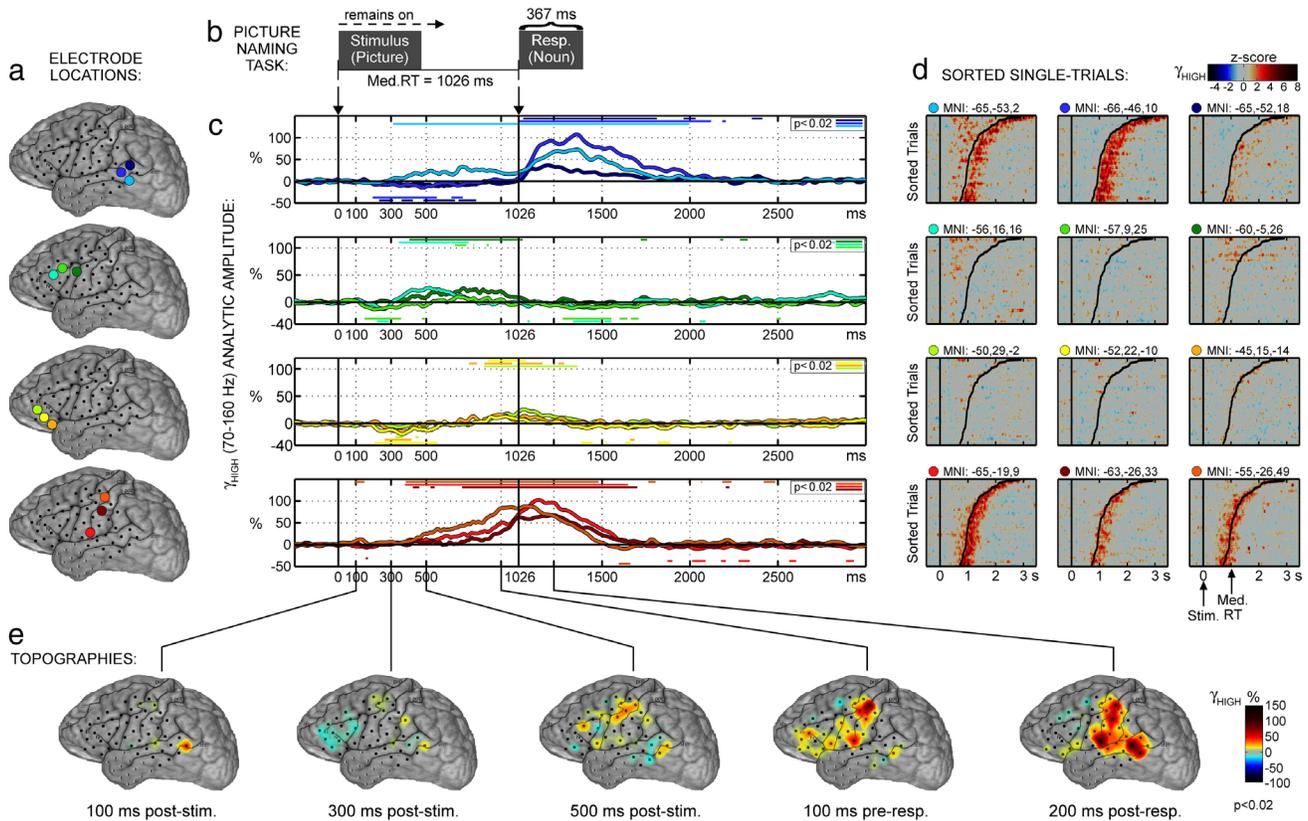


Figure 5. Broadband signal for picture naming for Patient 1. a. Locations of the recording sites. The colours correspond to the signal time courses in c. b. Trial events (stimulus and response). c. Broadband signal time courses. Vertical lines indicate stimulus onset and median response onset. Coloured horizontal lines indicate periods of significant amplitude change relative to the pre-stimulus baseline. d. Single-trial broadband amplitude sorted according to response time, which is indicated by the curved black lines in each plot. e. Topographies of the broadband signal over the latencies indicated below each topography. Reprinted from *NeuroImage*, 50/1, Edwards, E., Nagarajan, S. S., Dalal, S. S., Canolty, R. T., Kirsch, H. E., Barbaro, N. M., & Knight, R. T. “Spatiotemporal imaging of cortical activation during verb generation and picture naming”, 291-301, Copyright (2010), with permission from Elsevier.

Many iEEG production studies have focused on conceptually driven production tasks other than picture naming. For example, Williams Roberson and colleagues (2020) investigated verbal fluency and found increases in broadband activity over prefrontal regions in a timeframe attributed to conceptual search mechanisms (earlier than 600 ms prior to speech onset). Using a sentence completion task, Wang and colleagues (2021) found that sentences with more demanding lexical selection (i.e., with low cloze probability) were linked to increased activity in the LIFG as

well as to stronger interactions within the LIFG and between the LIFG and the left posterior temporal cortex. For iEEG studies examining semantic context-effects in picture naming, see Anders et al. (2019), Llorens et al. (2016), and Riès et al. (2017).

In a study involving iEEG, functional neuroimaging, and direct cortical stimulation (Forseth et al., 2018), auditory naming to definition and visual object naming were shown to be underlain by three stages of cortical activity, which were identified through consistent patterns of broadband activity preceding speech onset (see

also Kojima et al., 2013). The first stage involved modality-dependent sensory processing in early auditory or visual cortex. The second stage was characterized by heteromodal lexical semantic processing in the middle fusiform gyrus, the intraparietal sulcus, and the IFG. The final stage was linked to heteromodal articulatory planning in the supplementary motor area, mouth sensorimotor cortex, and early auditory cortex. Importantly, the identification of lexical-semantic-specific regions was corroborated by the significant reduction in broadband activity observed in these areas during control tasks involving nonsense stimuli (reversed speech or scrambled images). For a review of word-production studies using iEEG, see Llorens et al. (2011).

Sahin et al. (2009) examined the time course and spatial localization of grammatical encoding using LFPs recorded in and around the LIFG. Silently, participants either read nouns and verbs or produced their inflected forms following a preamble [e.g., overt inflection condition: *Yesterday they__ (walked)*; null inflection condition: *Everyday they __ (walk)*]. Three LFP components linked to distinct processing stages were reported: a first component, elicited ~200 ms after target presentation, was taken to index lexical access because, among other reasons, it was sensitive to the lexical frequency of target words. A second component, which became apparent ~320 ms post-target onset, was linked to grammatical operations, as it was exclusively sensitive to inflection requirements of the task. The third component, visible around 450 ms post-target onset, was taken to reflect phonological, phonetic, and articulatory programming processes because it varied according to the number of syllables in the words and because it differentiated between the overt inflection condition, which required

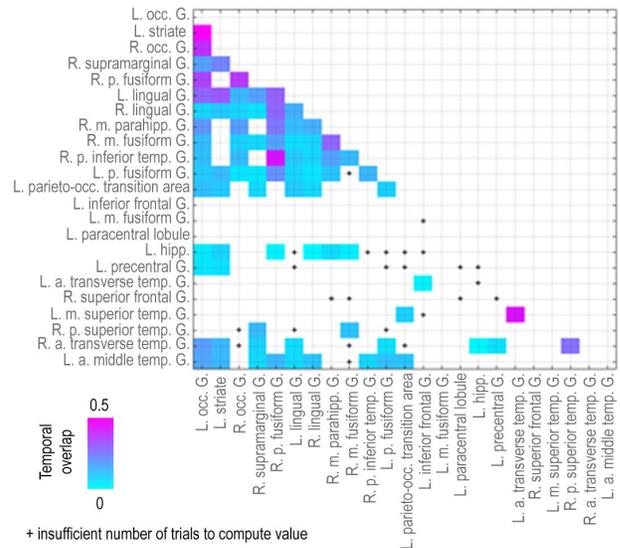


Figure 6. Overview of the temporal overlap between regions that were found to be consistently active during picture naming. Overlap was computed for cases when the total number of trials showing significant activity was at least 20 (an insufficient number of trials is indicated by the + sign). The maximum temporal overlap observed in the supra-threshold activity between all pairs of regions post-picture onset is indicated by the color coding. L. = left; R. = right; G. = gyrus; occ. = occipital; p. = posterior; m. = medial; (para)hipp. = (para)hippocampus; temp. = temporal; a. = anterior. Figure modified from courtesy of Anne Sophie Dubarry.

additional phonological programming, and the other two conditions, which did not.

As one of the approaches used by Lee and colleagues (2018) to investigate the production of functional morphemes (e.g., past tense “-ed” attached to a verb), the authors analyzed LFPs from posterior brain regions during a structured word production task. Sites within the posterior STG and below the temporo-parietal junction showed differences in LFPs starting ~1.5 s before speech onset between a condition in which morphological manipulations were required (e.g., overtly producing “walked” after seeing “Yesterday, we [walk]”) and a control condition in which only the

articulation of the target word was necessary through reading aloud (e.g., producing “walked” after “Yesterday, we [walked]”). Combined with evidence from lesion evaluations and focal cortical disruption through electrical current stimulation, these results were interpreted as being consistent with the idea that the posterior STG implements a discrete step during word production that is specific to functional morphological operations.

Chartier and colleagues (2018) investigated articulatory dynamics during continuous speech production by relating broadband iEEG responses to vocal tract movements. The authors found that specific neural populations in the ventral sensorimotor cortex (vSMC) encode articulatory kinematic trajectories (AKTs), which are coordinated to make specific vocal-tract configurations, and which exhibit out-and-back trajectory profiles with damped oscillatory dynamics. In addition, the AKTs encoded in the vSMC represented the coarticulation of successive AKTs, indicating that the vSMC does not locally encode phonemes, as these would elicit similar neural activity regardless of phonemic or kinematic contexts.

In summary, by capitalizing on the high temporal and spatial resolution afforded by iEEG and on the broadband signal as an index of task-specific cortical activity, studies have provided insights into *when* different brain areas are involved in speaking. More recently, studies have also started to relate these patterns to more specific word production operations, contributing to the refinement of language production models.

6. Some (methodological) challenges

Empirical results are only as good as the quality of the methods from which they are derived. Over the past decade, it has become clearer that the scalp MEEG signal can be analyzed in combination with

overt production, but special considerations during analysis are needed to allow for sound interpretations. Some methodological approaches have been proposed to deal with speech-related artefacts in the signal (Ouyang et al., 2011; Porcaro et al., 2015; Vos et al., 2010), but little validation work and cross-methods comparisons have been conducted. Although critical, this is a challenging task for obvious reasons, and also because it is not immediately clear what such validations should consist of (see also Piai, Riès, & Knight, 2015, for a critical discussion of this and related issues).

Nonetheless, recent studies have tackled methodological issues involved in the analysis of the electrophysiological signal closest to articulation onset. For example, Fargier and colleagues (2018) showed that a phonetic feature such as voicing of a word’s initial plosive (i.e., /p/ vs. /b/) influence the EEG signal in a way consistent in timing with the duration of the voicing period preceding the burst (see also Ouyang et al., 2016). Conducting microstate ERP analysis on data related to a delayed pseudoword production task, Jouen and colleagues (2021) confirmed previous observations that articulation starts several hundred milliseconds before vocal onsets and that the duration of the articulatory to acoustic onset interval (AAI) varies according to initial phoneme. As its main contribution, this study also shows that the onset of a specific ERP microstate may index the onset of articulation, as the microstate covered the known articulatory to acoustic gap for specific onset phonemes. Thus, future studies could be better equipped to visualize AAI differences between conditions, making it easier to investigate the final stages of speech production and to distinguish between cognitive and motor processes.

A different type of challenge is faced by the field of cognitive neuroscience more broadly: The extent to which neural data can be used to address

cognitive questions remains debatable. This is because cognitive theories in their strict sense are not formulated at the same level as the information provided by neural data (see for discussion Poeppel, 2012). Given that this is not an issue with electrophysiology in particular, we will not address it further, but refer the reader to relevant discussions for example by Page (2006) and Coltheart (2013).

6.1. The value of MEEG-based measures

While it may be argued that brain data cannot be (easily) used to address theories about cognition, there are some cases in which MEEG-based measures can be of particular value (although not necessarily to adjudicate between cognitive theories in their strict sense). Besides the future directions already mentioned throughout the chapter, here we highlight other avenues that exemplify the relevance of electrophysiological data.

One special case is offered by the excellent temporal resolution of the MEEG signal. In some cases, one may wish to know when a particular brain area is engaged in a task. Even though there are criticisms to using the MEEG signal to make claims about when precisely things happen (e.g., Piai, 2016), one can be absolutely certain that a particular modulation (in a brain area) occurred during word planning versus after articulation. Haemodynamic-based measures, by contrast, do not allow for this level of temporal scrutiny, so one can never easily disentangle word planning from post-articulation processes using these measures. Therefore, MEEG-based measures may provide special information in the context of language production. One concrete example is illustrated by discussions about the recruitment of the right hemisphere in cases of left-hemisphere brain damage. If one finds right-hemisphere recruitment

using MEEG-based measures, one can be certain about whether this recruitment happened during word planning or after articulation (e.g., Piai et al., 2017, 2020).

Some scholars have argued that MEEG-based measures such as neural oscillations may provide a way to elucidate how general neuronal computational principles support language (e.g., Friederici & Singer, 2015; Piai & Zheng, 2019). Under this view, the finding of overlapping brain regions between two different domains is not enough evidence in favour of shared mechanisms between these domains. Instead, stronger evidence for shared mechanisms would be provided by finding overlapping features in the multidimensional space that constitute the oscillatory signal, that is, space, time, spectrum, and direction of the modulation (see Piai and Zheng, 2019, for extensive discussion).

7. Conclusions

In this chapter, we have presented a selective review of studies focusing on spoken language production using electrophysiology. Albeit incompletely, we attempted to outline some of the evolution within the field, highlighting what kinds of questions researchers have focused on. From this exercise, it is clear that methodological rigor has to go hand-in-hand with our theoretical investigations, and that, given the relatively young age of this subfield, there is still much ground to cover. The emerging convergence of findings highlighted here will hopefully solidify as the field matures.

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