Differential temporo-spatial pattern of electrical brain activity during the processing of abstract concepts related to mental states and verbal associations

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1. Introduction

Concepts held in semantic long-term memory are basic units of cognition and support object recognition, action planning, problem solving and verbal communication (Tulving, 1972). They represent the meaning of objects, events or abstract ideas in a categorical fashion and constitute semantic word meaning (Humphreys et al., 1988; Kiefer and Harpauer, 2020; Levelt et al., 1999). Concepts refer to concrete objects (“table”) or actions (“to knock”), but also have referents, which cannot be perceived or acted upon, like mental or emotional states (“hope”), social constellations (“cooperation”), abstract ideas (“justice”), and scientific phenomena (“gravity”). The latter types of concepts, which do not refer to entities for which a direct sensory-motor experience is available, are traditionally termed “abstract concepts” (Paivio, 1986). In particular, knowledge representation of concepts with an abstract referent such as mental states is controversially discussed as outlined in the following sections.

The representation of abstract and concrete concepts can be quite naturally handled by amodal models. According to these traditional models in the cognitive sciences, concepts are viewed as abstract mental entities, different from the perceptual or motor brain systems (Anderson, 1983; Mahon and Caramazza, 2009; Pylyshyn, 1984; Quillian, 1969; Tyler and Moss, 2001): Modal sensory or motor features of objects and events are assumed to be transformed into a common amodal representation format, which codes conceptual information irrespective of its semantic content (Machery, 2007; Mahon and Caramazza, 2009; Weiskopf, 2010). At an anatomical level, amodal conceptual representations are thought to be held in heteromodal association cortex such as the anterior temporal (McClelland and Rogers, 2003; Rogers et al., 2004) or posterior temporal cortex (Hoffman et al., 2012), so-called semantic hubs (Binder, 2016). Activation of modal representations during language comprehension or conceptual thinking is only an auxiliary or concomitant process after the amodal concept has been accessed, due to semantic elaboration (Mahon and Caramazza, 2008), imagery (Machery, 2007) or passive spreading of activation to input or output levels (Mahon, 2015a, 2015b).
Abstract concepts are particularly challenging for grounded cognition or embodied cognition theories, which assume that conceptual representations are essentially rooted in modal experiential information (e.g., Barsalou et al. 2003; Borgh and Binkofski 2014; Glenberg and Kaschak 2002; Kiefer and Harppainter 2020; Kiefer and Pulvermüller 2012; Lakoff and Johnson 1999; Pulvermüller 2005). According to this class of theories, distributed modal experiential representations of external (perception) and internal states (proprioception, emotion and introspection) as well as actions are thought to establish conceptual representations and thus play a functional role in conceptual cognition. At a neuroanatomical level, it is proposed that activation of cell assemblies in distinct brain areas responsible for sensory, motor, introspective and emotional processes constitute the concept. These modal systems are situationally recruited as a function of task demands and situations, resulting in a flexible composition of features contributing to the concept (e.g., Barsalou et al. 2018; Hoenig et al. 2008; Kemmerer 2015; Kiefer and Harppainter 2020; Pulvermüller 2018).

Based upon neuroimaging findings on concrete concepts (Binder, 2016; Kuhnke et al., 2020; 2021 Popp et al., 2019), recent hybrid models of conceptual representations propose a hierarchy of processing circuits ranging from lower-level modality-specific cortex over bi-, tri- or multimodal regions up to top-level amodal areas in heteromodal cortex, presumably indexing increasing levels of abstraction (e.g., Binder 2016; Fernandino et al. 2016; Garagnani and Pulvermüller 2016; Hoffman et al. 2018; Kiefer and Harppainter 2020; Kuhnke et al. 2020; Patterson et al. 2007; Pulvermüller et al. 2010).

In contrast to concrete concepts, the representation of abstract concepts, which lack a physical referent, are difficult to explain by grounded cognition theories at a first glance and seems to require an amodal or verbal representation. In fact, past theorizing was dominated for a long time by the view that abstract concepts require amodal (Mahon and Caramazza, 2009) or verbal representations (Paivio, 1986) based upon the statistical co-occurrence of words in language (Connell, 2019; Dove, 2016; Hoffman, 2016; Hultén et al., 2021).

In order to accommodate the notion that language plays an important role for establishing the meaning of abstract concepts, refined grounded cognition approaches assume that linguistic information complements modal information. The Language and Situated Simulation Theory (LASS, Barsalou et al. 2008) suggests that verbal associations might provide a rapid short-cut to the meaning of a word, when it takes too much time to simulate sensory-motor information. According to Words as Social Tools Theory (WAT, Borghi and Binkofski, 2014; Borghi and Zarcone, 2016), abstract concepts are frequently acquired via verbal communication and are therefore grounded in the language system including motor areas required for articulation.

In further expanding the grounded cognition account, abstract concepts might not only be grounded in the perception of external events and in actions, but also in the introspection of internal mental states and mentalizing social constellations (Barsalou and Wiemer-Hastings, 2005; Borgh and Binkofski, 2014; Harppainter et al., 2018; Kiefer and Harppainter, 2020) as well as in the processing of affective information (Herbert et al., 2009; Vigliocco et al., 2014; Ziegler et al., 2018).

In contrast to the domain of concrete concepts (for reviews, see Barsalou 2008; Kiefer and Pulvermüller 2012; Pulvermüller and Fadiga 2010), several studies on abstract concept processing seem to falsify grounded cognition theories: When comparing brain activity to abstract vs. concrete concepts, a stronger recruitment of left hemisphere language regions for abstract concepts, particularly of the middle and superior temporal gyrus as well as of the left inferior frontal gyrus, was found (e.g., Binder et al. 2005; Hultén et al. 2021), in congruency with the importance of verbal information including verbal associations for establishing the meaning of abstract concepts (for a meta-analysis, see Wang et al. 2010).

However, rating and property listing studies characterizing the semantic content of abstract concepts demonstrated their heterogeneity (Barca et al., 2017; Barsalou and Wiemer-Hastings, 2005; Ghio et al., 2013; Harppainter et al., 2018; Lynott and Connell, 2013; Troche et al., 2014; van Dantzig et al., 2011; Villani et al., 2019; Zdravilova et al., 2018). Abstract concepts should therefore not be viewed as homogeneous category (for a recent review see, Conca et al. 2021). For instance, the semantic content of a large set of 296 abstract concepts was determined in a property listing study (Harppainter et al., 2018). As predicted by refined grounded cognition theories, participants generated a substantial proportion of sensory-motor, introspective, emotional and social properties, in addition to verbal associations. Hierarchical cluster analyses of the generated properties demonstrated several subgroups of abstract concepts characterized by different property types. One cluster was dominated by introspective properties related to mental states (Harppainter et al., 2018). Rating studies also revealed a high relevance of introspective features for subgroups of abstract concepts (Troche et al., 2014; Villani et al., 2019).

The relevance of visual, motor and emotional features for some subgroups of abstract concepts has been documented in several neuroimaging and electrophysiological studies as well as in behavioral studies in brain-lesioned patients (for reviews, see Conca et al. 2021; Kiefer and Harppainter 2020). These studies suggest an involvement of the corresponding modal cortex in abstract concept processing (e.g., Desai et al. 2018; Dreyer et al. 2015; Harppainter et al., 2020a; Harppainter et al., 2020b, Herbert et al. 2009; Vigliocco et al. 2014).

Despite the acknowledged importance of mental states for the semantics of abstract concepts, only a few studies investigated neural activation in response to the processing of this subgroup of abstract concepts (Conca et al., 2021). This previous work suggests that abstract concepts related to mental states are semantically processed in brain networks subserving mentalizing and action simulation including dorso- and ventro-medial prefrontal cortex, orbito-frontal cortex, inferior frontal cortex, posterior cingulate cortex and superior temporal cortex (Baron-Cohen et al., 1994; Desai et al., 2018; Huth et al., 2016; Wilson-Mendenhall et al., 2013), the insula (Ponz et al., 2014; Ziegler et al., 2018), and face motor areas (Dreyer and Pulvermüller, 2018). It has been suggested that activity in face motor areas in response to abstract mental concepts is related to the relevance of verbal communication for establishing the meaning of mental state words (see also, Borghi and Binkofski 2014).

This activity pattern to abstract mental state concepts is in line with earlier neuroimaging work on mentalizing and social interactions (Frith and Frith, 2006; Seymour et al., 2018; Wang et al., 2016). Activity in the fronto-parietal motor network might reflect simulated actions, which are used to decode mental states such as goals, intentions, thoughts, desires and beliefs (Arioli and Canessa, 2019; Canessa et al., 2012) and support mental perspective taking (Wang et al., 2016). A brain network comprising cingulate gyrus, superior frontal gyrus, insula, superior temporal gyrus as well as the precuneus is known to be involved in various forms of mentalizing (Frith and Frith, 2006) including theory of mind, social interactions and empathy (Abu-Akel and Shamy-Toory, 2011; Arioli and Canessa, 2019; Canessa et al., 2012; Geiger et al., 2019; Singer et al., 2009).

A recent ERP study investigated the time course of abstract verb processing by comparing electrical brain activity to abstract mental, abstract emotional, abstract nonbodily state, and concrete verbs in a syntactic classification task (Muraki et al., 2020). Differences across abstract mental state and abstract nonbodily state verbs were found over the fronto-central and the parietal and occipital scalp 400 ms after target onset. Distributed source estimation in specified regions of interest (ROI) suggested larger activity for abstract mental state verbs than for abstract nonbodily state verbs in bilateral parietal cortex, bilateral somatosensory cortex, bilateral precuneus and right temporal pole. The relatively late onset of differential ERP activity across verb categories beyond 400 ms, however, does not preclude the possibility that neural processes related to mental states arose after an amodal concept has been accessed. Earlier ERP research suggests that post-conceptual processes such as semantic integration start around 400 ms in anterior
temporal areas, a putative amodal semantic hub (Kiefer et al., 2011), as indexed for instance by the semantic congruency effect on the N400 ERP component (Kutas and Hillyard, 1980). The N400 component is also assumed to index activation of an amodal concept (Grainger and Holcomb, 2009). As an approximate estimation, activity in modal brain regions before 300 ms most likely reflects access to conceptual features (Ponz et al., 2014).

Hence, previous work suggests that abstract concepts related to mental states are semantically processed in brain networks subserving mentalizing and action simulation, in support of refined grounded cognition theories. However, there were only few earlier studies, which have several limitations. Firstly, sometimes only one single abstract concept was investigated (Wilson-Mendenhall et al., 2013). Secondly, analysis was occasionally performed only in regions of interest, but not in the whole brain (Dreyer and Pulvermüller, 2018; Muraki et al., 2020). Thirdly, one ERP study investigating processing of mental state abstract verbs observed late ERP effects (Muraki et al., 2020). This suggests that activity in brain regions involved in introspection and mentalizing may reflect post-conceptual processing. However, the syntactic categorization task, which does not involve conceptual processing, may have reduced conceptual processing and thus have masked an earlier onset of differential activity. Furthermore, abstract nonbodily state verbs, which served as control category to mental state verbs in this study, were mainly characterized by the absence of an identifiable semantic content rendering a clear interpretation of this comparison difficult. Given the scarcity of available evidence on the neural correlates of processing abstract mental state concepts (Conca et al., 2021) and given the mentioned limitations of earlier studies, the time course of brain activity to well-defined sets of abstract mental state concepts and of abstract control concepts deserves further investigation.

In the present ERP study, we therefore measured the time course of neural processing in response to abstract mental state concepts and to verbal association concepts as abstract control category. We adopted a theory-driven approach previously used for investigating concrete (Kiefer et al., 2008; Trumpf et al., 2014) or abstract concepts (Harpainter et al., 2020a; Harpaintner et al., 2020b) and compared electrical brain activity to well-defined subsets of abstract mental state (e.g., “will”) and verbal association concepts (e.g., “justice”) with a pre-determined feature content obtained in a previous property listing study (Harpainter et al., 2018). These sixty abstract nouns were presented during a lexical decision task (word/pseudoword decision), which mainly requires retrieval of lexical information, but implicitly probes semantic processing (Dilkina et al., 2010; Kiefer, 2002). Note that the two stimulus sets were carefully matched for confounding linguistic and conceptual variables including valence, arousal as well as modal semantic content.

In addition to scalp ERPs, source estimates of underlying volume brain activity were determined to reveal spatio-temporal clusters of greater electrical brain activity to abstract mental state vs. verbal association concepts, and vice versa. Based upon refined grounded cognition theories (e.g., Borghi et al. 2017; Kiefer and Harpaintner 2020; Muraki et al. 2020; Wilson-Mendenhall et al. 2013), we hypothesized that abstract mental state concepts would enhance activity in areas related to mentalizing such as lateral and medial prefrontal cortex, insula, temporo-parietal junction and precuneus, but also in visuo-motor areas subserving action simulation as previously identified in studies on mentalizing and social interaction (e.g., Arioli et al. 2018; Cabeza and St Jacques 2007; Geiger et al. 2019; Seymour et al. 2018). Abstract verbal association concepts should enhance activity in linguistic brain areas encompassing temporal and inferior frontal areas (Wang et al., 2010). The observation of early activity in areas related to mentalizing would confirm that the semantic content of mental state concepts is processed in modal experiential brain networks in line with grounded cognition theories. Such results would further support the notion of the heterogeneity of abstract concepts and would emphasize the importance to carefully determine their semantic content.

2. Methods

2.1. Participants

Forty-seven healthy, right-handed (according to Oldfield 1971), native German-speaking students from Ulm University participated in the study. Three participants were excluded from the analysis due to a high mean reaction time or high mean error rate (exclusion criterion: individual mean RT or ER above or below the sample mean +/- 2SD). Final analysis included electrophysiological data of 44 participants (Mage = 21.84 years, range = 18–29 years, 32 females). Participants were free from a history of neurological or psychiatric disorders according to self-report. Participants gave written informed consent and were paid 17 Euros or two course credits for participation. Procedures were approved by the Ethical Committee of Ulm University and adhere to the tenets of the Declaration of Helsinki.

2.2. Stimuli

Sixty abstract words served as critical stimuli in the lexical decision task (for the stimulus list, see the Supplementary Material). Additional 60 pseudowords served as distractors. Half of the abstract words (30 words) had a strong link to introspective and internal mental state properties (mental state, MST, concepts), whereas the other half (30 words) had a strong link to verbal association properties (verbal association, VAS, concepts), as determined on the basis of a previous property generation study (Harpainter et al., 2018). In this study, participants (not participating in the present study) had to generate properties for 296 abstract concepts, which were subsequently categorized according to modality-specific and verbal contents (for further details see Harpaintner et al., 2018). Sixty pseudowords were created by replacing one consonant and one vowel of abstract words not used in the experimental conditions by another consonant and vowel. Pseudowords thus consisted of meaningless but pronounceable letter strings (e.g., “Reuchsum”). Abstract concepts and pseudowords were matched with regard to word length. The chosen MST (e.g., “will”, “surprise”) and VAS (e.g., “fate”, “justice”) abstract concepts were carefully matched with regard to possible confounding conceptual features (visual, acoustic, motor, tactile, gustatory, valence, arousal, concreteness/abstractness, familiarity) and psycholinguistic variables (age of acquisition, word length, lemma frequency, character bi- and trigram frequency). Conceptual feature norms as well as familiarity, valence, arousal and concreteness/abstractness ratings were taken from the previous property listing study (Harpainter et al., 2018). Lemma frequency, character bi- and trigram frequency were determined according to the dlexDB database (Heister et al., 2011), age of acquisition norms were taken from Kuperman et al. (2012).

In Table 1, we report mean values, standard deviations and effect sizes of the matched conceptual and psycholinguistic variables for MST and VAS abstract concepts as recommended by Sassenhagen and Alday (2016). In order to complement these descriptive statistics, we also report p values resulting from two-tailed unpaired t-tests, although the use of statistical tests to evaluate the matching of word sets has been recently criticized because this procedure rests on the acceptance of the null hypothesis, which is problematic for statistical reasons (Sassenhagen and Alday, 2016).

2.3. Procedure

The study was carried out in a sound attenuated, dimly illuminated and electrically shielded cabin. Participants were comfortably seated in an upright position and were instructed via detailed written and verbal instructions. To ensure complete understanding of the instructions, participants had to practice the task in a preceding training session with 15 stimuli not used in the main experiment. Participants were furthermore encouraged to blink only during the breaks and to stay relaxed during
the whole EEG-recordings in order to avoid ocular and movement artifacts. Participants were seated in front of a cathode-ray-tube computer screen at a distance of 70 cm resulting in a viewing angle subtending about 3° horizontally and 1° vertically. Words of the MST andVAS categories as well as the pseudowords were presented in a randomized order with white font (font size: 24 point character height) on a black background in the middle of the screen synchronous with the screen refresh (refresh rate: 16 ms). Each trial started with a fixation cross of 500 ms duration followed by the target lasting for 400 ms. Participants had to decide whether the presented stimulus was a real German word or a pseudoword. They responded with the index and middle fingers of their right hand by pressing buttons on a response keyboard. If the stimulus was a real word, participants pressed the left button with the index finger. In response to pseudowords, participants pressed the right button with the middle finger. Participants were instructed to decide as fast and accurately as possible. The screen remained blank for 1400 ms after the presentation of the stimulus. At the end of each trial three hash marks lasting for 2000 ms indicated a pause between the trials. Stimulation presentation and behavioral data acquisition were controlled by the Presentation 18.1 software package (NeuroBehavioral Systems, Berkeley, USA).

### 2.4. EEG recording, signal extraction, source analyses and data analysis

Scalp voltages were continuously recorded at a sampling rate of 500 Hz (low-pass filter: 100 Hz, 24 dB/octave attenuation) using BrainAmp AC coupled amplifiers and BrainVision Recorder software (BrainProducts, Gilching, Germany) from 64 equidistant Ag/AgCl electrodes mounted in an elastic textile cap (EasyCap, Herrsching, Germany). An electrode between FCz and Cz was used as recording reference, the ground electrode was positioned between AFz and Fz. Eye movements were monitored with supra- and infra-orbital electrodes and with electrodes on the external canthi. All EEG electrode impedances were maintained below 5 kΩ.

EEG data were processed offline by BrainVision Analyzer 2.0 (BrainProducts, Gilching, Germany). After digitally filtering (high-pass: 0.1 Hz, 12 dB/octave, low-pass: 30 Hz, 24 dB/octave, 50 Hz notch filter) the EEG data, Independent Component Analysis (ICA) was used to remove ocular artifacts (Makeig et al., 1997): Components reflecting ocular activity were determined by visual inspection and subsequently excluded. Hjorth Nearest Neighbors interpolation replaced data of single noisy electrodes by interpolating data of four surrounding electrodes. Continuous EEG data were segmented starting 150 ms prior to target presentation, which served for baseline correction, and ended 1000 ms after target onset. Segments exhibiting amplitudes of more than 70 μV or less than -70 μV, showing voltage steps greater than 50 μV/ms were automatically excluded as artifacts from analyses. The remaining artifact-free EEG segments of trials with correct responses were averaged synchronous to the onset of the target separately for each word category in each participant in order to extract individual ERPs. Thereafter, these ERPs were re-referenced to the average reference (Bertrand et al., 1985). ERPs to pseudowords, which served as distractors, are reported in the Supplementary Results.

To test for significant differences between MST and VAS conditions across all electrode sites within the entire EEG recording epoch, cluster permutation tests were performed using BESA Statistics 2.0 (BESA GmbH, Graefelfingen, Germany). To avoid the problem of multiple comparisons due to a large number of time points and channels, BESA statistics makes use of a combination of permutation testing and data clustering (Maris and Oostenveld, 2007). The initial statistics used for the subsequent permutations were based on two-tailed paired samples t-tests comparing ERP data in response to MST vs. VAS abstract concepts. A cluster value consisting of the sum of all t-values derived from a random permutation procedure (10,000 permutations; neighbor distance 3.8 cm) was determined for each cluster such that the significance of the initial clusters could be determined based on the distribution of the calculated cluster values after permutation. Level of significance was defined as p < .05, corrected for multiple comparisons. The mean number of artifact-free EEG segments of trials with correct responses was 29.46 (SD = 0.88) for MST and 29.46 (SD = 0.76) for VAS abstract concepts. A two-tailed paired samples t-test confirmed that the number of segments did not significantly differ between conditions (t(43) = 0, p = 1, 95%-CI [-0.32; 0.32]).

Neural source estimates of the ERPs in the MST and VAS conditions across the entire recording epoch were determined using standardized, unweighted minimum norm computations in the whole brain 3D volume based on the sLORETA method (Pascual-Marqui, 2002) implemented in BESA 6.1 (BESA GmbH, Graefelfingen, Germany). Minimum norm source activity estimates in the 3D volume were calculated in each individual for each time point and condition using a standardized realistic finite element head model (FEM). Distributed volume images were regular-

### Table 1

Mean values and standard deviation (in parenthesis) of conceptual and psycholinguistic variables for MST and VAS abstract concepts. Effect sizes and p values refer to the comparison of MST and VAS word sets. Shown are only conceptual properties with a proportion larger than 0.01. MST: mental states; VAS: verbal associations.

<table>
<thead>
<tr>
<th>Proportion MST properties</th>
<th>VAS abstract concepts</th>
<th>MST vs. VAS (p-values)</th>
<th>Cohen’s d</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.57 (0.08)</td>
<td>0.20 (0.11)</td>
<td>P &lt; 0.001</td>
<td>d = 3.85</td>
</tr>
<tr>
<td>0.16 (0.09)</td>
<td>0.53 (0.09)</td>
<td>p &lt; 0.001</td>
<td>d = 4.11</td>
</tr>
<tr>
<td>0.10 (0.07)</td>
<td>0.12 (0.08)</td>
<td>P = 0.217</td>
<td>d = 0.27</td>
</tr>
<tr>
<td>0.02 (0.03)</td>
<td>0.01 (0.02)</td>
<td>p = 0.225</td>
<td>d = 0.39</td>
</tr>
<tr>
<td>0.09 (0.06)</td>
<td>0.08 (0.05)</td>
<td>P = 0.435</td>
<td>d = 0.18</td>
</tr>
<tr>
<td>0.05 (0.06)</td>
<td>0.04 (0.05)</td>
<td>p = 0.887</td>
<td>d = 0.18</td>
</tr>
<tr>
<td>2.29 (0.40)</td>
<td>2.47 (0.66)</td>
<td>p = 0.205</td>
<td>d = 0.33</td>
</tr>
<tr>
<td>4.48 (0.68)</td>
<td>4.26 (0.76)</td>
<td>p = 0.256</td>
<td>d = 0.31</td>
</tr>
<tr>
<td>0.25 (1.76)</td>
<td>0.40 (1.71)</td>
<td>p = 0.741</td>
<td>d = 0.09</td>
</tr>
<tr>
<td>2.87 (0.77)</td>
<td>2.58 (0.91)</td>
<td>p = 0.188</td>
<td>d = 0.34</td>
</tr>
<tr>
<td>8.43 (1.83)</td>
<td>8.87 (2.4)</td>
<td>p = 0.428</td>
<td>d = 0.21</td>
</tr>
<tr>
<td>9.27 (2.41)</td>
<td>8.33 (2.63)</td>
<td>p = 0.157</td>
<td>d = 0.37</td>
</tr>
<tr>
<td>5041.00 (6909.06)</td>
<td>5994.33 (5539.69)</td>
<td>p = 0.558</td>
<td>d = 0.15</td>
</tr>
<tr>
<td>362987.27 (165087.07)</td>
<td>310918.99 (162117.72)</td>
<td>p = 0.223</td>
<td>d = 0.32</td>
</tr>
<tr>
<td>144211.02 (79224.88)</td>
<td>138353.36 (58107.43)</td>
<td>p = 0.745</td>
<td>d = 0.08</td>
</tr>
</tbody>
</table>

a Depicted p-values were obtained using two-tailed unpaired t-tests.
b Scales of the items: concreteness/abstractness: six-point Likert scale with the poles “abstract” (1) and “concrete” (6); familiarity: six-point Likert scale with the poles “low familiarity” (1) and “high familiarity” (6); valence: six-point Likert scale with the poles “negative” (-3) and “positive” (+3); arousal: self-assessment manikins (Bradley and Lang, 1994) with the poles “weak” (1) and “strong” (5). c According to Kuperman et al. (2012). d According to Heister et al. (2011).
ized using the truncated singular value decomposition (TSVD) approach with a 0.03% threshold. In brief, in the TSVD regularization approach, all singular values smaller than the percentage of the maximum singular value specified in this threshold are set to zero. The singular values above this threshold are used to calculate the volume source images. The threshold value determines the extent of regularization of the obtained source images. A larger threshold results in a stronger regularization (many singular values are set to zero) and can lead to potentially smeared source images. A threshold of 0.03% (default value in BESA) is thus a reasonable tradeoff between too strong regularization (smeared volume images) and too small regularization (scattered volume images with multiple maxima within one region). The obtained volume source activity images for each time point and condition in each participant were subjected to cluster permutation testing using BESA Statistics 2.0 (BESA GmbH, Graefelfing, Germany) to reveal significant differences between MST and VAS conditions in time and source space. Level of significance was defined as \( p < .05 \), corrected for multiple comparisons. Cluster permutation tests in source space were restricted to the time interval, in which significant scalp ERP differences were observed, in order to reduce the number of comparisons. The initial statistics used for the subsequent permutations (10,000 permutations) were based on one-tailed paired samples \( t \)-tests comparing source activity in 3D space in response to MST vs. VAS abstract concepts and vice versa. These one-tailed \( t \)-tests reveal brain areas with larger source activity in one condition compared to the other. For the obtained significant clusters, anatomical labels and Brodmann areas (BA) of anatomical locations (in Talairach coordinates) of absolute and local peak activities within clusters were determined using the Talairach Daemon (Lancaster et al., 2000). Given the low spatial resolution of EEG, the reported anatomical labels and BAs only provide an approximate estimation of the neuroanatomical location of brain electrical sources.

With regard to the behavioral data of the lexical decision task, the mean error rates (ER) and the mean correct reaction times (RT) were calculated for each participant and each condition (MST, VAS, pseudowords). Individual reaction times that differed more than two standard deviations of the individual mean were excluded from RT analyses. Furthermore, participants with individual mean RT or ER across conditions above or below the sample mean +/- 2SD were excluded from analyses (see also the participants sections). Repeated measures analyses of variance (ANOVA) were carried out in order to investigate whether RT or ER differed between the conditions. Level of significance was defined as \( p < .05 \). Behavioral and EEG data are available at https://osf.io/6jm2r.

### 2.5. Post-experimental ratings

Subsequent to the lexical decision task, a rating study was conducted to validate the differential relevance of internal states/ emotions and verbal associations for MST and VAS abstract concepts in the study sample. Participants were seated at a table in a quiet room outside the EEG recording cabin and were instructed via detailed written and verbal instructions to perform ratings using a questionnaire. The questionnaire contained the 60 abstract concepts of the lexical decision task and additional 30 abstract concepts as fillers, also taken from the previous property listing study (Harpainter et al., 2018). The fillers had intermediate proportions of property listings with regard to MST and VAS properties, respectively. Each concept had to be rated regarding the relevance of internal states including the experience of emotions as well as verbal associations on a six-point-Likert-scale. Higher values represented higher relevance of internal states or verbal associations. The questionnaire was printed in three versions with a randomized order of the abstract concepts to exclude order effects. Differences between MST and VAS abstract concepts regarding their relevance of internal states and verbal associations, respectively, were tested with two-tailed paired \( t \)-tests on mean scores of the ratings per concept set (MST, VAS).

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>Mean ER in %</th>
<th>Mean RT in ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>MST abstract concepts</td>
<td>1.74 (2.92)</td>
<td>575 (84.04)</td>
</tr>
<tr>
<td>VAS abstract concepts</td>
<td>1.74 (2.54)</td>
<td>579 (78.32)</td>
</tr>
<tr>
<td>Pseudowords</td>
<td>3.07 (3.45)</td>
<td>652 (91.13)</td>
</tr>
</tbody>
</table>

### 3. Results

#### 3.1. Post-experimental ratings

Post-experimental ratings of the MST and VAS abstract concepts confirmed the expected differential relevance of internal states vs. verbal associations for these word categories. The ratings regarding the relevance of internal states showed higher scores for MST vs. VAS abstract concepts (\( M = 4.06, SD = .68 \) vs. \( M = 3.20, SD = .61 \), respectively; \( t(43) = 9.98, p < .001, 95\%-\text{CI} \) [0.68, 1.03], \( d_{\text{diff}} = 1.51 \)). The ratings regarding verbal associations showed higher scores for VAS vs. MST abstract concepts (\( M = 3.96, SD = .69 \) and \( M = 3.35, SD = .68 \), respectively; \( t(43) = 6.90, p < .001, 95\%-\text{CI} \) [0.43, 0.80], \( d_{\text{diff}} = 1.03 \)).

#### 3.2. Behavioral data of the main experiment

Analysis of behavioral data yielded a mean ER of 2.18% (SD = 3.02%) and a mean correct RT of 602.24 ms (SD = 84.50 ms) showing that participants performed the task carefully (outliers not considered in the RT analysis: 3.4%) Table 2 displays mean ER and mean RT for the two word categories and the pseudowords. A repeated measures ANOVA on mean correct RT revealed significant differences between words and pseudowords (\( F(2,86) = 122.38, p < .001 \)). According to Bonferroni post-hoc tests, pseudowords differed significantly from both abstract concept categories (\( p < .001 \)), while MST and VAS abstract concepts did not significantly differ from each other (\( p = 1 \)). A repeated measures ANOVA on mean ER yielded a main effect of stimulus category (\( F(2,86) = 3.68, p = .029 \)). However, differences between conditions were not statistically reliable in Bonferroni post-hoc tests (abstract concept categories vs. pseudowords: all \( p > .063 \); MST vs. VAS abstract concepts: \( p = 1 \)).

#### 3.3. Electrophysiological data

##### 3.3.1. Analysis of scalp ERPs

Cluster permutation tests revealed significant differences between the processing of MST vs. VAS abstract concepts in five electrode clusters (Table 3, Figs. 1 and 2). One cluster (cluster 1) with more positive ERPs to VAS concepts and four clusters (clusters I-IV) with more positive ERPs to MST concepts. Cluster 1 showing more positive scalp potentials in response to VAS vs. MST abstract concepts spanned a time window from 244 to 634 ms. It comprised fronto-central electrodes mainly distributed over the left hemisphere.

Clusters I to IV were characterized by more positive scalp potentials in response to MST vs. VAS abstract concepts. The clusters I, II and III emerged shortly after each other: Cluster I lasted from 194 to 266 ms, cluster II from 266 to 426 ms and cluster III from 412 to 680 ms. All three clusters included electrodes over posterior portions of the scalp including temporal, occipital and parietal regions. Cluster IV ranging from 726 to 856 ms comprised left fronto-central electrodes.

##### 3.3.2. Analysis of volume source estimates

Cluster permutation tests were performed to compare volume source activity estimated by sLORETA (Pascual-Marqui, 2002) in response to MST and VAS conditions (Table 4 and Fig. 3). Statistical analyses of source estimates yielded one cluster (cluster 1) showing greater activity...
to VAS concepts within a time window from 194 to 210 ms. Cluster 1 was located in left occipital areas comprising lingual gyrus (BA 18) and fusiform gyrus (BA 19) with peak activity in the left lingual gyrus (BA 18).

Analyses of source estimates revealed greater source activity to MST vs. VAS concepts in five clusters (clusters I–V). In a time window of 212–264 ms, cluster I comprised left parietal areas as well as lateral and medial prefrontal areas. The left parietal subcluster encompassed the left superior parietal lobule (BA 7) extending medially to the precuneus (BA 7). The prefrontal subcluster included the left and right superior frontal gyri (BA 6, 8), the right cingulate gyrus (BA 24) as well as the left rostral middle frontal gyrus (BA 10). Peak activity of cluster I was found in the left superior parietal lobule (BA 7). Between 262 and 414 ms, cluster II comprised right fronto-parieto-temporal areas including postcentral gyrus (BA 2, 43), precentral gyrus (BA 4), but also, at a more inferior location, superior temporal gyrus (BA 41) extending posteriorly to the temporoparietal junction. A subcluster in left medial occipito-parietal areas encompassing the precuneus (BA 7) was also part of cluster II. Peak activity of cluster II was obtained in the right postcentral gyrus (BA 2). In a time window of 416–500 ms, cluster III comprised mainly the right insula (BA 13), but extended to precentral (BA 4) and postcentral (BA 3) gyri. Peak activity was observed in the right insula (BA 13). In a time window of 520–590 ms, cluster IV comprised voxels in a frontal midline area including right cingulate (BA 24) and medial frontal gyri (BA 10). Peak activity was yielded in the right cingulate gyrus (BA 24). Finally, in the time window of 756–822 ms, cluster V included voxels in right lateral prefrontal areas. Peak activity was obtained in the right caudal middle frontal gyrus (BA 6).

4. Discussion

In the present ERP study, we investigated the time course of brain activity elicited by the processing of abstract concepts related to mental states and to verbal associations, respectively, during a lexical decision task. Volume source estimates of scalp ERP were calculated to reveal the spatio-temporal dynamics of abstract concept processing as a function of the abstract word set. This work served to test the prediction of refined grounded cognition theories that abstract concepts are processed in differential brain areas depending on their semantic feature content. These activity differences were assumed to emerge relatively early (<300 ms) suggesting that they reflect access to conceptual features and not later post-conceptual processing (Machery, 2007; Mahon, 2015). As expected, we observed differential scalp ERP effects between abstract mental state and verbal association concepts starting at 194 ms after word presentation. However, ERP effects continued in time intervals beyond 300 ms. Verbal association concepts elicited a relatively more positive potential over the frontal scalp, whereas mental state concepts evoked a more positive potential over the occipito-parietal scalp. These distinct scalp topographies suggest that mental states and verbal association abstract concepts are processed in partially dissociable brain areas. The early onset of these effects indicate that activity differences most likely reflect access to distinct conceptual features processed in different brain areas, although effects in time intervals later than 300 ms indicate that post-conceptual processing might also contribute. The time course of brain activity is discussed in detail below.

In line with the distinct scalp topographies for abstract mental state and verbal association concepts, analyses of volume source estimates suggested differential activity in several brain regions for these sets of abstract concepts. For verbal association concepts, analyses of source estimates indicated increased activity starting at 194 ms after word presentation in a left occipital cluster with peak activity in lingual gyrus extending to fusiform gyrus. Hence, contrary to our expectation of stronger activity in inferior frontal and temporal language areas, processing of verbal association concepts was associated with enhanced activity in higher-level visual cortex. Estimated source activity in left fusiform gyrus (~22, -59, -7) (Jobard et al., 2003), presumably involved in the processing of visual word form (Cohen and Dehaene, 2004; Dehaene and Cohen, 2011; McCandliss et al., 2003). Peak activity of this cluster in lingual gyrus was more distant (3.7 cm). The present source estimates of increased occipital activity to VAS concepts had a more medial and posterior location compared to the neuroanatomical location of the visual word form area in the meta-analysis of fMRI data (Jobard et al., 2003). However, due to the limited spatial resolution of ERP source estimates (Regan, 1989), this source may nevertheless reflect activity of the visual word form area.
Fig. 1. Results of cluster permutation tests. Depicted are ERPs to abstract mental state concepts and to abstract verbal association concepts averaged over all electrodes of the respective cluster. Electrodes included in the clusters are shown in Table 3. Grey rectangles indicate the time window of the cluster. The y-axes indicates the onset of the target, while the dashed vertical line shows its offset.

despite the differences in precise neuroanatomical coordinates. Hence, increased activity to verbal association concepts in left occipital cortex might reflect the retrieval of associated visual word forms. In line with this interpretation, left occipito-temporal cortex was active during the learning of new verbal associations (Sperling et al., 2001) and during a verbal fluency task (Birn et al., 2010), suggesting a role of left occipital cortex in processing verbal associations. The earlier onset of this effect, compared to increased activity in response to mental state concepts as discussed below, could indicate that verbal associations are activated more rapidly than conceptual features related to action, perception and introspection as suggested previously (Barsalou et al., 2008).

However, an alternative interpretation of this left occipito-temporal activity to VAS concepts should also be considered: Occipito-temporal cortex is generally involved in higher-level vision (Price and Devlin, 2003). Specifically, an earlier fMRI study (Harpaintner et al., 2020a) found left fusiform and lingual cortex to be activated by abstract concepts with a high relevance of visual features. Left occipital activity might therefore alternatively reflect retrieval of visual concep-
Fig. 2. Results of cluster permutation tests comparing scalp ERPs to abstract mental state and abstract verbal association concepts. Depicted are the topographic voltage difference maps of each cluster at the time point of the largest t-value across all electrodes. Only electrodes with significant t-values ($p < .05$) at the specific time point are depicted (for all electrodes per cluster see Table 3).

...tual information. Given that VAS and MST concepts were matched for concreteness and visual properties, it is unlikely that VAS concepts are more imageable. Furthermore, the early onset and offset of increased occipital activity renders an interpretation in terms of imagery implausible. However, it is possible that increased occipital activity was driven by the visual semantic content of the words associated with the VAS concepts. For instance, for the VAS concept “justice” participants might have stored the associated word “Justitia”, which refers to the allegoric woman holding a sword and a scale in her hands. In our coding scheme (Harpaintner et al., 2018), word associations were not further distin...
guished according to their semantic content. As spatial resolution of ERP source estimates is too low for a localization of the activated occipital area with a precision of a few millimeters, the present ERP source analyses are not suited to determine, whether increased left occipital source activity to VAS concepts reflects activation of the visual word form area or of more general visual areas supporting visual conceptual feature retrieval.

In the meta-analysis by Wang et al. (2010), abstract concepts elicited greater activity in classical perisylvian language areas of frontal and temporal cortex compared to concrete concepts. In contrast to the present results with abstract VAS concepts, activity increases in left occipito-temporal cortex to abstract concepts were absent in this meta-analysis. This discrepancy can be explained by the fact that concrete concepts, the comparison category to abstract concepts in this
meta-analysis, elicited greater activity in the fusiform gyrus, i.e. a region within occipito-temporal cortex. Hence, relatively greater occipito-temporal activity to concrete concepts most likely has masked activity in this region to abstract concepts. In our study, abstract VAS concepts were contrasted with a different abstract concept category (abstract MST concepts) so that increased activity in occipital areas could be detected.

The absence of expected differential activity in classical perisylvian language areas of frontal and temporal cortex could be due to a comparable recruitment of these areas for both abstract concept types. In line with this interpretation, the present set of mental state concepts received a substantial proportion of verbal associations in the property listings (0.16), albeit of course lower than the selected set of verbal association concepts (0.53) due to the criteria for stimulus selection. Furthermore, it is possible that measuring the relevance of verbal associations via feature listings and ratings do not capture other aspects of linguistic processing such as the importance of inner speech or the use of language to clarify the content of an abstract concept (Borghi and Binkofski, 2014).

The latter two aspects of linguistic processing, which are important for abstract concepts (e.g., Fini et al., 2021), might be equally important for the present sets of abstract mental state and verbal association concepts.

For abstract mental state concepts, analyses of source estimates suggested increased activity in a sequence of five spatio-temporal clusters. The first cluster (212–264 ms) comprised left parietal areas (superior parietal lobule extending to the left precuneus) as well as lateral (bilateral superior frontal gyrus and left middle frontal gyrus) and medial prefrontal areas (right anterior cingulate gyrus). The second cluster (262–414 ms) included right post- and precenral gyri, the superior temporal gyrus extending to the temporo-parietal junction, and a subcluster encompassing the left precuneus. The third cluster (416–500 ms) comprised the right insula extending to precentral and postcentral gyrus. The fourth cluster (520–590 ms) comprised the right cingulate and medial frontal gyri. The late fifth cluster (756–822 ms) included the right middle frontal gyrus. Hence, processing of mental state abstract concepts increased activation in a network of areas including lateral and medial prefrontal areas, pre- and postcentral gyri, insula as well as lateral and medial parietal cortex in a time range between 212 and 822 ms. Similarly to the analysis of scalp ERPs, analyses of volume source estimates indicated that activity differences presumably reflect both early conceptual and later post-conceptual processes.

Frontal and parietal motor areas showed enhanced estimated source activity in response to mental state concepts with a relatively early onset. Starting at 212 ms, increased estimated source activity was observed in left parietal regions including the superior parietal lobule and neighboring intra-parietal sulcus. These areas have been related to visuo-motor processing during action observation (Sim et al., 2015) and to the retrieval of conceptual action information (Kuhnke et al., 2020). In addition, primary sensory-motor areas in right pre- and postcentral gyrus showed also increased estimated source activity with a slightly later onset at 262 ms. Increased source activity in this visuo-motor network ended at 500 ms. In line with previous research (Dreyer and Pulvermüller, 2018; Muraki et al., 2020), processing of abstract mental state concepts recruited sensory-motor areas also in the present study. We would like to note that abstract mental state concepts and verbal association concepts of the present word set were matched with regard to the proportion of modal properties, including visual, tactile and motor properties generated in the norming study (Harpaintner et al., 2018). This indicates that increased sensory-motor activity most likely arises from the processing of mental states and cannot simply reflect preponderance of this feature information in the mental state concepts used in the present study. We discuss the putative role of the visuo-motor system for the processing of mental state concepts in more detail below.

In contrast to the previous ERP study using a non-semantic syntactic categorization task, in which source activity in motor regions emerged later around 400 ms (Muraki et al., 2020), motor activity had a much earlier onset in the present study, in which participants performed a lexical decision task. This suggests that motor activity in response to mental state concepts can also arise in relatively early processing stages, given that the task probes at least some implicit semantic processing as the lexical decision task (Dilkina et al., 2010; Kiefer, 2002). Motor activity during abstract concept processing has been related to the recruitment of articulatory programs, because abstract concepts are mainly acquired through verbal communication (Barca et al., 2017; Borghi and Binkofski, 2014). For instance, increased activity in face-motor areas to mental state concepts supports this hypotheses (Dreyer and Pulvermüller, 2018). It is possible that inner speech or use of language to clarify the meaning of the concept was more relevant for mental state than for verbal association concepts, although property listings and ratings showed a higher relevance of verbal information for verbal association concepts. As already discussed above, property listings or ratings might not fully capture these aspects of linguistic information associated with a concept. Unfortunately, the low spatial resolution of ERP source analyses and the missing body part specific motor localizer did not allow us to test the specific involvement of face-motor areas in the present study.

However, as estimated source activity to mental state concepts was not restricted to the primary motor cortex, but comprised a large fronto-parietal motor network, it seems not very likely that this widespread motor activity exclusively reflects recruitment of articulatory motor programs. We therefore propose that motor activity to abstract mental state concepts might also reflect simulations of actions occurring in situations, to which mental state concepts are applied (Barsalou et al., 2018). For instance, simulated actions might be used to decode mental states such as goals, mental perspectives, desires and beliefs as suggested by neuroimaging work in mentalizing and social interactions (Arioli and Canessa, 2019; Canessa et al., 2012; Wang et al., 2016). Hence, given the importance of the motor system for various aspects of mentalizing, processing concepts related to mental states might involve action simulation within the motor system as one cognitive basis of mentalizing.

In addition to a sensory-motor network, abstract mental state concepts elicited increased estimated source activity in a brain network comprising cingulate gyrus, medial, middle and superior frontal gyri, insula, superior temporal gyrus as well as the precuneus in line with previous neuroimaging work (Baron-Cohen et al., 1994; Desai et al., 2018; Huth et al., 2016; Ponz et al., 2014; Wilson-Mendenhall et al., 2013; Ziegler et al., 2018). These areas are known to be involved in various forms of mentalizing (Frith and Frith, 2006) including theory of mind, social interactions and empathy (Abu-Akel and Shamay-Tsoory, 2011 Arioli and Canessa, 2019; Canessa et al., 2012; Geiger et al., 2019; Singer et al., 2009). As deep and superficial brain electrical sources can occasionally produce similar scalp potential distributions, the depth of an estimated source can be imprecise. Nevertheless, despite the relatively low spatial resolution of electrophysiological recordings, earlier combined EEG/fMRI studies (e.g., Bledowski et al. 2004; Linden et al. 1999; Minati et al. 2008) and a recent validation study with intracranial recordings (Citherlet et al., 2020) have shown that source estimates of electrical scalp potentials can identify activity in brain structures such as the cingulate cortex, precuneus and insula, which are not directly located on the cortical surface (for a discussion of the possibility to identify even subcortical sources, see Krishnaswamy et al. 2017).

Although the precise function of these areas for mentalizing are not fully understood, it has been suggested that dorsal parts of lateral and medial prefrontal cortex including dorsal anterior cingulate cortex process cognitive aspects of mental states such as the analysis of thoughts, intentions, desires and beliefs, whereas orbito-frontal lateral and ventro-medial partitions of prefrontal cortex support affective aspects of mentalizing such as the assignment of emotional value (Abu-Akel and Shamay-Tsoory, 2011). Right superior temporal regions, in particular the posterior temporal sulcus and the temporo-parietal junction, may serve to interface the mentalizing and visuo-motor networks and have supposedly a role in decoding intentions from actions by initial parsing of visuo-spatial information (Arioli and Canessa, 2019). The right temporo-parietal junction has also been identified as cru-
cial network hub for mental perspective taking and social cognition (Martin et al., 2020; Seymour et al., 2018; Wang et al., 2016). The precuneus has been frequently associated with various forms of mentalizing (Abu-Akel and Shamay-Tsoory, 2011; Schneider-Hassloff et al., 2015), but seems to play a particular role in self-referential thought (Abu-Akel and Shamay-Tsoory, 2011; Cabeza and Jacobs, 2007). The precuneus as well as the temporal-parietal junction have been suggested to provide the input for the prefrontal mentalizing network (Abu-Akel and Shamay-Tsoory, 2011). The insula has been found to be active in a variety of emotional tasks (for a review, see Singer et al. 2009) including the processing of emotion words (Ponz et al., 2014; Ziegler et al., 2018), and is involved in relating bodily states to subjective feelings (Damasio, 1994). Given its role in the mapping of bodily states and subjective feelings, the insula has also been suggested to support emotional empathy with others (Bird et al., 2010; Singer et al., 2009; Singer et al., 2004).

The time course of increased estimated source activity in this mentalizing network considerably differed between areas and spanned both early and late time windows suggesting that processing reflects both initial conceptual access and later post-conceptual processes such as elaboration or spreading activation. Activity enhancement to mental state concepts in the precuneus, in the cingulate gyrus, superior frontal gyrus, rostral middle frontal gyrus (onset at 212 ms) as well as in the superior temporal gyrus (onset at 262 ms) emerged relatively early. This early onset of activity increases in parts of the mentalizing network suggests that processing in these areas contributes to the initial access to the abstract mental state concept. Increased cingulate gyrus activity was observed again in later time intervals (520–590 ms). Activity increases in the insula, medial frontal gyrus, and caudal middle frontal gyrus had an onset beyond 400 ms suggesting that processing in these areas reflects later semantic elaboration after initial concept activation. In particular, cingulate, medial frontal and caudal middle frontal gyrus exhibited increased activity in late intervals (520 ms and later). Possibly, retrieval of bodily states associated with subjective feelings including empathy in the insula leads to an elaboration of the initially established abstract mental state concept by further processing in prefrontal mentalizing circuits.

Thus, the processing of mental state concepts may depend on two temporal overlapping, but partially separable processes: (i) Simulation of actions, to which the mental state concepts apply, starts in the conceptual access phase and is completed at about 500 ms in the initial part of the semantic elaboration phase. (ii) Mentalizing, i.e. processing of thoughts, intentions, desires and beliefs related to the simulated actions, also starts in the conceptual access phase, but continues during the entire semantic elaboration phase until about 800 ms. Although only a few earlier neuroimaging and ERP studies investigated mental state concepts (for a review, see Conca et al. 2021), the results of the present study provide converging evidence that mental state concepts are processed in modal brain systems. More importantly, our ERP results considerably extend this earlier work by showing that processing of abstract mental state concepts depends on a sequence of activity in visuomotor and mentalizing brain circuits in early and later phases of semantic processing. Hence, although generally in support of refined grounded cognition theories (Barsalou and Wiemer-Hastings, 2005; Borghi and Binkofski, 2014; Harpainter et al., 2018; Kiefer and Harpainter, 2020; Vigliocco et al., 2014), our results partly confirm criticism raised by proponents of amodal approaches (Machery, 2007; Mahon, 2015b) claiming that activity in brain circuits related to perception, action and introspection might arise from post-conceptual processing.

The present study also further confirms the notion that abstract concepts are highly heterogeneous and differ with regard to their semantic content (Barca et al., 2017; Barsalou and Wiemer-Hastings, 2005; Conca et al., 2021; Desai et al., 2018; Gio, 2013; Harpainter et al., 2018; Kiefer and Harpainter, 2020; Lynott and Connell, 2013; Muraki et al., 2020; van Dantzig et al., 2011; Villani et al., 2019; Zdrazilova et al., 2018). In particular, our results show that a theoretically and empirically predefined set of abstract mental state and verbal association concepts elicits a dissociable pattern of electrical brain activity in both time and space. Our findings specifically support a multiple representation view of abstract concepts (Borghi et al., 2017; Conca et al., 2021; Harpainter et al., 2018; Kiefer and Harpainter, 2020; Muraki et al., 2020; Wilson-Mendenhall et al., 2013; Zdrazilova et al., 2018): Compared to verbal association concepts, mental state concepts seem to be based on rich representations established by action and mentalizing neural circuits. The meaning of abstract concepts is thus not exclusively established by verbal associations or linguistic representations as suggested previously (Dove, 2016; Paivio, 1986). The present research also highlights the importance of investigating the neural processing of sets of abstract concepts with a defined semantic content. Future studies could elucidate neural processing of sets of abstract concepts with dominance of other semantic feature content such as social constellations or specific emotions.

When interpreting the present data, several limitations should be considered. Firstly, although MST and VAS abstract concepts were closely matched for a variety of conceptual and linguistic variables, there were some slight non-significant differences in particular with respect to lemma frequency and number of letters. Note that the use of statistical tests to evaluate the matching of word sets, a common procedure in psycholinguistic research, has been recently criticized for various reasons, in particular because it rests on the statistically problematic acceptance of the null hypothesis (Sassenhagen and Alday, 2016). Furthermore, the variation of feature content in the present word sets with regard to mental states and verbal associations is gradual or subtle, and the number of stimuli per category (n = 30) is relatively low. In order to control for the influence of confounding variables due to potential insufficient stimulus matching, it has been recently suggested to conduct single trial analyses with these nuisance variables as additional predictors of no-interest (Sassenhagen and Alday, 2016). Unfortunately, ERP analyses require averaging of EEG epochs across trials so that the proposed single trial analyses could not be calculated in the present study. Nuisance variables such as word length could be included at the single trial level in the statistical model of future fMRI studies.

However, it is unlikely that the observed ERP differences between MST and VAS concepts reflect effects of nuisance variables due to insufficient matching for several reasons. As shown in Table 1, effect sizes of the differences in the proportion of MST and VAS properties of the MST and VAS word sets were very large (d > 3.85), whereas effect sizes for all nuisance variables were generally small (d < .39). We would also like to emphasize that the differential contribution of mental states vs. verbal association to the word categories, as a priori determined by the property listings, was confirmed by the post experimental ratings in the participant group of this study, demonstrating the validity of the conceptual feature manipulation. Even for the post-experimental ratings, effect sizes, albeit smaller than for the initial matching (d > 1), were still much larger than those of the nuisance variables such as word frequency and word length differences (d < .39). It is also noteworthy that RT and ER to MST and VAS abstract concepts were identical or quite similar indicating a comparable level of processing difficulty. If anything, RT to MST abstract concepts was 4 ms faster than to VAS abstract concepts, despite of slightly greater word length and lower lemma frequency of MST concepts. Typically, the opposite is observed: Participants need more time to respond to longer and less frequent words (Brysbaert et al., 2018; King and Kutas, 1998; New et al., 2006). Furthermore, the time course and topography of the present ERP differences with regard to MST and VAS concepts differed from typical word length and frequency effects (for a review, see Hauk and Pulvermüller, 2004): Word frequency and word length ERP effects are observed already in earlier time ranges than in the present experiment within the time windows of the occipital P1 (80–125 ms, word length effects) and N170 (150–190 ms, word length and word frequency effects) ERP components (e.g., Brown et al. 1999; Hauk and Pulvermüller, 2004; King and Kutas 1998), but rarely extend beyond 400 ms after stimulus onset. Such early occipital effects were
entirely absent in the present data, in which ERPs to MST and VAS concepts diverged between 194 and 856 ms. As a further validation of the present electrophysiological data, we compared ERPs to words and pseudowords. These control analyses yielded the typical lexicality ERP effect suggesting an adequate signal-to-noise ratio despite the relatively low number of stimuli per condition (see Supplementary Results).

Secondly, electrophysiological recordings of brain activity from the scalp offer an excellent temporal resolution, but a poor spatial resolution (Regan, 1989). The precise anatomical location of the volume source estimates should therefore be viewed with caution. A confirmation of the presently observed brain electrical sources underlying abstract concept processing using fMRI measurements is recommended, although fast decaying brain activity might not always be captured by this neuroimaging method due to its poor temporal resolution. Given the higher spatial resolution of fMRI, localizer tasks probing body part specific actions, mentalizing and processing of verbal associations, respectively, should be used in future fMRI studies, to better functionally characterize neural circuits involved in the processing of mental state and verbal association concepts compared to the present electrophysiological study.

Thirdly, measurements of brain activity only provide correlative evidence, but are not informative with regard to the causal or functional relevance of the identified neural circuits for abstract concept processing. We cannot exclude that activity in the identified neural circuits occurs only concomitantly, but does not play a functional role in abstract concept processing (e.g., Mahon 2015b). Future studies using transcranial magnetic stimulation (Kuhnke et al., 2020), investigation of brain-lesioned patients (Trumpp et al., 2013) or behavioral interference paradigms (Shebani and Pulvermüller, 2013), are therefore needed to demonstrate a functional role of these areas for the processing of mental state vs. verbal association concepts (but see, Dreyer et al., 2015).

Finally, as statistically analyses compared electrical source activity between mental state and verbal association concepts, common activity to both sets of abstract concepts in conceptual hub regions such as the anterior temporal lobe or in perisylvian language regions could not be detected. Recent hybrid models of conceptual representations combine modality-specific and multimodal circuits with amodal conceptual hubs (Binder, 2016; Fernandino et al., 2016; Garagnani and Pulvermüller, 2016; Hoffman et al., 2018; Kiefer and Harppaintner, 2020; Kuhnke et al., 2020; Patterson et al., 2007; Pulvermüller et al., 2010; Simmons and Barsalou, 2003), presumably indexing increasing levels of abstraction (e.g., Kiefer and Harppaintner 2020; Kuhnke et al. 2020). Common recruitment of conceptual hub or language regions for both sets of abstract concepts is therefore possible.

In conclusion, the present study observed a differential temporal-spatial pattern of estimated electrical source activity in response to the processing of semantically predefined abstract mental state vs. verbal association concepts. Analyses of source estimates of verbal association concepts revealed early (onset 194 ms), but short-lived activity increases (offset 210 ms) compared to mental state concepts in left occipital regions. Increased occipital activity might reflect retrieval of visual word form or access to visual conceptual features of associated words. Enhanced estimated source activity to mental state concepts was obtained with an onset of 212 ms in visuo-motor (superior parietal, pre- and post-central areas) and mentalizing networks (lateral and medial prefrontal areas, insula, precuneus, temporo-parietal junction), which extended to later time windows. In particular the prefrontal mentalizing network showed persistent source activity increases beyond 500 ms compared with verbal association concepts. In line with refined grounded cognition approaches (Borgli et al., 2017; Harppaintner et al., 2018; Kiefer and Harppaintner, 2020; Muraki et al., 2020; Wilson-Mendenhall et al., 2013; Zdrazilova et al., 2018), the present research supports a multiple representation view of abstract concepts, which includes linguistic, visuo-motor and introspective brain circuits. Differential activity in these feature-specific circuits depends on the relevance of features for a given concept.

The present study thus further confirms the proposal that the semantic content of abstract concepts is heterogeneous and involves representations in distinct neural circuits depending on their semantic feature content. In extending previous work, our results show that processing abstract mental state concepts is accomplished by rapidly emerging, but sustained activity in visuo-motor and mentalizing networks. Although the functional relevance of these brain circuits for establishing the meaning of mental state concepts remains to be demonstrated, our results indicate that highly abstract mental state concepts are not exclusively based on linguistic or amodal representations. The present research also highlights the importance of investigating sets of abstract concepts with a defined semantic content.

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Ethics approval
All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional ethical review board of Ulm University and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The ethics committee of Ulm University, Ulm, Germany (106/14), approved the study protocol.

Data availability
Behavioral and EEG data are available at https://osf.io/6jm2r.

Declaration of Competing Interest
All authors declare that they have no conflict of interest.

Supplementary materials
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Credit authorship contribution statement
Markus Kiefer: Conceptualization, Visualization, Formal analysis, Writing – original draft, Writing – review & editing, Supervision, Project administration. Lena Pielke: Investigation, Data curation, Formal analysis, Writing – review & editing. Natalie M. Trumpp: Conceptualization, Visualization, Investigation, Data curation, Formal analysis, Writing – review & editing.

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