



# Are metaphors embodied? The neural evidence

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## Abstract

Abstract concepts can potentially be represented using metaphorical mappings to concrete domains. This view predicts that when linguistic metaphors are processed, they will invoke sensory-motor simulations. Here, I examine evidence from neuroimaging and lesion studies that addresses whether metaphors in language are embodied in this manner. Given the controversy in this area, I first outline some criteria by which the quality of neuroimaging and lesion studies might be evaluated. I then review studies of metaphors in various sensory-motor domains, such as action, motion, texture, taste, and time, and examine their strengths and weaknesses. Studies of idioms are evaluated next. I also address some neuroimaging studies that can speak to the question of metaphoric conceptual organization without explicit use of linguistic metaphors. I conclude that the weight of the evidence suggests that metaphors are indeed grounded in sensory-motor systems. The case of idioms is less clear, and I suggest that they might be grounded in a qualitatively different manner than metaphors at higher levels of the action hierarchy. While metaphors are unlikely to explain all aspects of abstract concept representation, for some specific abstract concepts, there is also nonlinguistic neural evidence for metaphoric conceptual organization.

## Introduction

Any comprehensive theory of the conceptual or semantic system requires an account of abstract concept representation. Abstract concepts can be defined as those that cannot be perceived directly with the five senses (vision, hearing, touch, taste, and smell). Concepts such *idea* or *theory* are abstract in this sense in that they have no direct sensory correlates, as opposed to concrete concepts such as *chair* or *thunder*. While embodiment theories, which suggest that concepts are grounded in action-perception systems (Barsalou, 2008; Kiefer & Pulvermüller, 2012), apply clearly to concrete concepts, it is not obvious how they can account for abstract concepts.<sup>1</sup> Abstract lexical concepts, treated as a single broad category, activate mid- and anterior superior temporal sulcus, and inferior frontal gyrus, relative to concrete concepts (Wang et al., 2010). These are multi-functional areas that can be argued to represent embodiment of abstract concepts. However, these areas are also prominently related to executive and phonological processes, and hence

the precise nature of grounding is less clear. A number of accounts that seek to explain grounding abstract concepts have been proposed (Borghi et al., 2019; Desai et al., 2018; Kiefer & Harpaintner, 2020; Villani et al., 2019). These theories point out that abstract concepts do not form a unified category, but rather come in many flavors. Different kinds of abstract concepts can be grounded through their reference to events and situations, meta-cognition, interoception, and emotion.

A different and influential answer to the puzzle of abstract concepts is provided by appealing to analogical mappings between abstract and concrete domains in the form of metaphors. If abstract concepts can be understood in terms of analogical or metaphoric mappings with concrete concepts, which do have sensory-motor features, then abstract concepts can be grounded as well. Figurative language (e.g., metaphors, idioms, proverbs, and clichés) is pervasive in everyday life. Pollio (1977) estimated that people use about 6 non-literal fixed expressions per minute of discourse, including 1.8 new metaphors and 4.08 conventionalized metaphors. This may reflect an underlying metaphorical structure of the conceptual system. This view was promoted

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<sup>1</sup> This is not meant to imply that other theories, such as the amodal symbol view, do in fact account for abstract concepts. Whether other theories can account for either concrete or abstract concepts is indeed not clear, but this is a separate question that will not be addressed here.

most prominently by Lakoff and colleagues, as Conceptual Metaphor Theory (CMT; Lakoff, 1993; Lakoff & Johnson, 1980, 1999). A conceptual metaphor is a projection of the basic experiential structure from concrete domains of experience (e.g., action, spatial orientation, and movement) to abstract domains (e.g., mental processes, morality, and mathematics). For example, the abstract concept of *understanding* something can be based on the action of *grasping* an object. This is manifested in the linguistic metaphor *grasping an idea*, with mappings *grasping*  $\Leftrightarrow$  *understanding* and *object*  $\Leftrightarrow$  *idea*. This view suggests that metaphors are embodied. Abstract ideas are not just *described* in terms of concrete domains when we use metaphors in language, but are *understood* in terms of concrete domains.

Several criticisms of CMT and related theories have also arisen (McGlone, 2007, 2011; Murphy, 1996, 1997). A central question that arises from this proposal is whether metaphor in language necessarily translates to metaphor in conceptual processing. A familiar or conventional metaphor can develop a homonymous sense. A metaphor such as *He grasped the idea* may be processed similarly to *He understood the idea*, because *grasp* has two distinct meanings: one reflecting the action and the other completely abstract, *to understand*. The embodiment account suggests, instead, that *He grasped the idea* should be processed similarly to *He grasped the handle*. The *understand* sense of *grasp* is processed through cross-domain mapping with action, and is not abstract.

Here, I review evidence from neuroimaging, brain stimulation, and lesion studies that speaks to the debate on embodiment of metaphoric and idiomatic language. A significant body of behavioral research exists that has been reviewed elsewhere (Gibbs, 2011) and will not be addressed here (for an alternative view, see Casasanto & Gijssels, 2015). I begin with a tutorial review of factors to consider when designing and evaluating neuroimaging studies. We will use these criteria to evaluate studies, address some of the criticisms of this neuroimaging work, and attempt to distinguish between valid and weak criticisms.

## Metaphor embodiment

A number of neuroimaging studies have examined the question of the grounding of metaphoric language, typically by comparing metaphoric sentences to non-metaphoric ones, and examining differential activations in relevant sensory-motor brain areas. A typical comparison is between a sensory-motor metaphor (MET; e.g., *The man grasped the idea*;

*She had a rough day*) and an abstract or non-sensory-motor control sentence (ABS; *The man wanted the item*; *She had a bad day*). Literal action sentences are also often used (LIT<sup>2</sup>; *The man grasped the handle*; *She had a rough blanket*). The key prediction is that sensory-motor areas should be activated for MET > ABS contrast, and they should also be seen for the LIT > ABS contrast. Note that the contrast MET > LIT is not particularly useful with respect to the question of embodiment. This contrast is relevant to the question of how metaphors are processed in general, which is an important but separate issue. The embodiment view predicts a null result in sensory-motor cortex (roughly equal activation for MET and LIT), or somewhat stronger activation for LIT.

Another approach used in several studies is to omit the ABS condition and instead use semantic somatotopy. For example, arm-related and leg-related metaphors can be used as controls for each other by comparing them directly. Here, more activation in an arm region of interest (ROI) is predicted for MET-arm, and more in the leg ROI for MET-leg. Other types of sentences used in studies are idioms (IDI; *The country lifted the veil on its nuclear program*) and fictive motion sentences (FIC; *The road goes through the valley*). FIC sentences are motion metaphors that use an inanimate agent that could not literally undergo the described motion. Here, I will adopt this terminology (MET, LIT, ABS, IDI, FIC) to describe various studies for clarity, instead of using the condition names used by the study authors. The notation A > B indicates areas activated more (e.g., those with a higher magnitude of BOLD response in an fMRI study) for condition A relative to condition B.

## How should neuroimaging studies be evaluated?

A number of factors affect the quality and reliability of results, and neuroimaging studies vary widely on some of the dimensions. I briefly review some of the important factors to keep in mind when designing and evaluating studies.

(1) *Characteristics of stimulus materials* Selecting a large number of metaphors and creating appropriate control conditions to study metaphor embodiment is a nontrivial, painstaking task that almost inevitably involves some form of compromise. Most neuroimaging studies have used sentence stimuli containing familiar metaphors. It is common to match conditions on a number of psycholinguistic variables, such as number of words, imageability/concreteness of content words, and word frequency. It is expected that MET and ABS conditions will have lower concreteness than LIT,

<sup>2</sup> Abstract sentences are also “literal” in that they are non-figurative. Here, the term LIT is reserved for non-figurative sentences that denote a concrete sensory-motor event, such as “throwing a ball.” ABS is used for literal sentences that denote events that do not directly entail action/perception, such as “considering my options.”

because of the use of abstract entities (e.g., *idea*). Another important consideration is the overall naturalness, familiarity, or processing difficulty of the sentences. Ideally, one wants these conditions to have similar level of difficulty. If one condition is more unnatural and difficult (typically MET), it would recruit additional executive resources that can lead to widespread activation, which would be incorrectly attributed as semantic. Many studies use either a rating or behavioral task to estimate and control for one or more of these interrelated variables (by matching conditions, or less ideally, by including it as a covariate in the analysis), which is a strength. Syntactic structure is another variable that ideally should be matched, but this is often difficult while maintaining similar naturalness and other constraints. It is virtually impossible to achieve syntactic match for idioms while maintaining naturalness for a large number of stimuli. Many studies use MET and ABS conditions are that equated on the number of words, but not syntactic structure (e.g., MET: *The man fell under her spell*; ABS: *The merchant was greedy and gluttonous*). Ideally, the ABS conditions should also have a meaning that is very similar to that of the MET condition (e.g., MET: *He grasped the idea*; ABS: *He understood the idea*). This is again difficult or impossible to achieve with a large number of stimuli while maintaining naturalness, and hence most studies do not have this feature. One approach is to use only a small number of sentences, which makes close matching on myriad variables more tractable. However, this necessitates repeating the stimuli several times for each participant, because using a large number of subjects, such as 50 or 60, which is commonly done in low-cost behavioral experiments, is usually infeasible in neuroimaging. This results in repetition suppression (reduced BOLD response for repeated stimuli) and a potentially less robust response. Investigators usually strike a compromise between equating the conditions for naturalness, processing difficulty, syntactic structure, and lexical variables such as frequency, at the expense of one of these variables.

Care should also be taken to distinguish between the specific types of figurative language under study. Some studies use a mix of metaphors, idioms, and proverbs, but label this condition ‘metaphor’ or ‘idiom,’ which can potentially be misleading (see “[Idioms](#)” for further discussion).

With respect to control conditions, some studies use a low-level baseline such as hash marks (‘#####’), false fonts (‘☉ ☪ ☭ ☮’), or fixation (‘+’). This does not control for phonological processing<sup>3</sup> and covert speech, which also engage motor and premotor areas. These are precisely the

areas of interest for action metaphors, creating a confound. While these sentence > low-level-baseline contrasts can create appealing visualizations by showing large activation clusters in the motor cortex, they can be misleading because they can result from phonology and covert speech rather than semantics. In these cases, critical comparisons are not MET > low-level-baseline, but contrasts that compare sentences with each other, such as MET-arm > MET-leg.

(2) *Definition of ROIs* To reduce number of statistical tests, investigators often pick one or more “region(s) of interest” (ROI) based on a hypothesis and restrict the analysis to these. Whole-brain analysis, compared to an ROI approach, has many desirable features. It is theoretically neutral, does not require an anatomical hypothesis, and can reveal expected as well as unexpected or novel results. It eliminates the suspicion that an ROI might have been picked in a post-hoc manner to produce the best results. However, in practice, it often tends to be too harsh or stringent, due to the large number of comparisons that require corrections. Relying only on whole-brain analyses would lead to many false negatives. Hence, most authors rely on hypothesis-driven ROIs, which are interrogated for predicted activation patterns. In a roughly decreasing order of desirability, ROIs can be defined in following ways. (1) Definition using a localizer task, and use at individual level. (2) Definition using a localizer task, use at a group level. (3) Regions (typically spherical) around peak coordinates from prior studies. (4) Anatomically defined small and large regions.

Due to anatomical precision at the subject level, (1) is the most desirable option especially if there is significant variability in the location of relevant functional regions, such as motion-sensitive region MT+. However, this option is not used frequently because of the significant added time to run a localizer task long enough to reliably detect a region in single subjects. If limited scanning time is available, spending a significant chunk on the localizer reduces the time available for the main experiment, resulting in a potentially weak result in the task of interest. Hence, most studies use options (2)–(4). It should also be noted that the localizer task and control conditions should be chosen appropriately, so that the resulting ROI is not too general or too restrictive.

Use of large ROIs, and averaging of signal within the ROI, can help reduce noise but is also susceptible to problems with reverse inference (Poldrack, 2006). That is, a large region is likely to have subdivisions involved in many functions, and even a small region can be multi-functional. Activation can be observed from nonspecific processes that are not well controlled for, such as attention, decision-making, or phonological and orthographic processing. On the other hand, it is possible to reduce the impact of such nonspecific processes using a carefully designed control condition. Defining well-circumscribed ROIs precisely, and in an a priori manner adds to the rigor of the study. The majority

<sup>3</sup> Many neuroimaging studies present sentence stimuli visually that are read silently. Note that this does not obviate the importance of controlling for phonology. Activation of phonological representations during reading is automatic and rapid (and similarly, orthography is activated to some extent by auditory word presentations).

of the metaphor studies discussed here have reasonable ROI definitions, coupled with appropriate control conditions, so that reverse inference is not a significant problem in those cases.

(3) *Statistical power* In recent years, there has been increased awareness of the importance of sample size, and potential problems caused by small sample sizes in studies in neuroscience and psychology (Button et al., 2013; Cremers et al., 2017; Pajula & Tohka, 2016; Turner et al., 2018). An experiment with a small number of subjects is susceptible to not only to false negatives, but also to false positives (Button et al., 2013). A sample size in terms of number of subjects between 20 and 30 is frequently recommended (Desmond & Glover, 2002; Murphy & Garavan, 2004; Pajula & Tohka, 2016) and is also practical. Sample size also depends on size of the effect, number of trials per subject, and anatomical variability of ROIs. Effect size can be expected to be small in case of metaphors compared to a well-matched control condition, while anatomical variability may be high especially higher order sensory-motor cortex. This is very different from contrasts that use very different conditions or have a sensory difference, such as finger tapping vs. rest, pictures vs. scrambled pictures, pain vs. little or no pain. Number of trials per condition is an equally important variable. Several neuroimaging studies of metaphor do not perform strongly in this department, using a relatively small sample size of 7–15 subjects and/or a small number of trials per condition.

Now, we turn to studies of metaphors in various sensory-motor domains, discussing first positive and then negative findings. Studies of idioms are discussed next. Table 1 summarizes these studies.

## Metaphors

### Action

Desai et al. (2011) used LIT, MET, and ABS sentences that were matched in syntactic structure as well as overall difficulty in a sensibility judgement task. The latter variable is an important potential confound, as more difficult or unfamiliar sentences can activate executive processing areas such as those related to attention and decision-making. The metaphors were non-idiomatic but conventional or familiar metaphors, and a meaningfulness judgment task (detect nonsense sentences inserted as catch trials) was used. In a whole-brain analysis, a higher order motor area associated with complex action planning and hand-object interaction in the left anterior inferior parietal lobe (aIPL) was activated not only for LIT > ABS, but also for MET > ABS (Fig. 1a).

aIPL has a well-established role in tool use, action planning, and goal-oriented action execution from numerous

neuroimaging and lesion studies (Binkofski et al., 2016; Buxbaum et al., 2007; Jax et al., 2006; Johnson-Frey et al., 2005; Peeters et al., 2013; Randerath et al., 2017; Vingerhoets, 2014) in addition to action semantics in single-word studies (e.g., Kuhnke et al., 2020). It is the central node in a tool use network formed by structural connections to posterior middle temporal and inferior frontal regions (Ramayya et al., 2010). The aIPL cluster covered both anterior supramarginal gyrus (aSMG) and the anterior end of the intraparietal sulcus (aIPS). Examining a large number of neuroimaging studies, Orban and Caruana (2014) found that aIPS was activated by observing a tool being grasped, while aSMG was activated by observation of moving the tool to achieve a goal (e.g., picking up an object). Similarly during action execution, they suggested that aIPS is associated with planning the grasp, and aSMG with planning the tool movement to achieve a goal. Ideomotor apraxia is often the result of damage to aIPL (Haaland et al., 2000; Jax et al., 2006). It results in impairments in imitating actions and gestures, pantomiming, recognizing object-related pantomimes, and planning object-related actions (Buxbaum et al., 2005; Goldenberg & Karnath, 2006; Varney & Damasio, 1987). TMS to aSMG causes a delay in planning goal-oriented actions, but not in responses to arbitrary stimuli (Tunik et al., 2008), and TMS to aIPS results in on-line adjustments of grasp (Tunik et al., 2005). Thus, converging evidence from neuroimaging, lesion, and brain stimulation studies point to a role of aIPL in planning and execution of goal-directed actions. Note that this region (aSMG and aIPS) is distinct from other regions of IPL, and also from other regions of SMG that are associated with functions such as phonological or multimodal processing. It is recruited in service of comprehension of both literal and metaphoric action language, presumably supporting higher order simulations of object-related actions.

The results also showed that the response in a primary motor area was inversely related to metaphor sentence familiarity, but not to abstract sentence familiarity, showing a familiarity  $\times$  condition interaction (Fig. 1a, right-most panel). This suggests a progression whereby primary motor cortex is recruited for processing relatively unfamiliar metaphors, and this reliance reduces as metaphors become more familiar. Note that very familiar (but non-idiomatic) metaphors still recruit the higher order action planning area in the left aIPL, which did not significantly vary with metaphor familiarity.

Desai et al. (2013) used MET, LIT, ABS, and IDI sentences. The sentences were longer and more varied in their syntactic structure compared to the Desai et al. (2011) study, due to inclusion of idiomatic sentences that were matched in length to other conditions. The MET > ABS comparison yielded similar results to that

**Table 1** A summary of studies of metaphor and idiom processing

Study	# subj	Conditions (sentences)	Domain	Presentation modality	# items per condition	Definition of ROIs	Task
<b>Neuroimaging studies</b>							
Romero Lauro et al. (2013)	24	Literal, metaphoric, idiomatic, fictive, abstract, upper and lower limb	Action/motion	Visual	21	Spherical regions centered on peaks from previous studies	Judge whether a task sentence is congruent with the main sentence using a button press
Boulenger et al. (2012)	18	Arm- and leg-related literal and idiomatic	Action (arm/leg)	Visual	38	Anatomical (hand drawn on average surface)	Answer occasional yes/no questions after catch trials
Raposo et al. (2009)	22	Arm and leg idiomatic	Action (arm/leg)	Auditory	28	Finger and foot movements	Word relatedness judgment on 50% the trials
Desai et al. (2011)	22	Literal, metaphoric, abstract	Action (hand/arm)	Visual	81	Whole brain, sequential hand movement	Sentence familiarity judgment after each run
Desai et al. (2013)	27	Literal, metaphoric, idiomatic, abstract	Action (hand/arm)	Visual	40	Whole brain, sequential hand movements	Sensibility judgment on 10% of the trials
Lacey et al., (2012)	7	Metaphoric and abstract	Texture	Auditory	54	Haptic and visual texture perception	Button press after each sentence has been understood
Aziz-Zadeh et al. (2006)	12	Literal, metaphoric for mouth, hand, foot	Action	Visual	5 items×8 repetitions	Videos of mouth, hand, and foot actions	Passive reading; recall after scan
Lacey et al. (2017)	12	Body part metaphors, body part literal; control literal corresponding to both	Body parts	Auditory	60	Visual, motor, and sensory localizers	Positive/neutral/negative valence judgement
Saygin et al. (2010)	13 <sup>a</sup>	Literal motion, fictive motion, static	Motion	Audiovisual (speaking face)	65	MT + localizer (moving vs. stationary dots)	Button press on detecting an anomalous sentence (~11% of trials)
Boulenger et al. (2009)	18	Literal, idiom for arm and foot	Action	Visual (RSVP)	38	Movements of finger or foot	Yes/no question with a button press after catch trials
Chen et al. (2008)	14	Literal motion, metaphoric motion, non-motive	Motion	Visual	35	Anatomically defined temporal and occipital regions	Sensibility judgment after each sentence
Wallentin et al. (2005a)	15	Literal motion, metaphoric motion, corresponding static	Motion	Auditory	32	Anatomically defined	Sensibility judgment after each sentence
Wallentin et al. (2005b)	18	Literal, metaphoric, fictive motion, nonsense	Motion	Visual and auditory	40	Whole brain	Sensibility judgment after each sentence
Lai and Desai (2016)	22	Literal motion, spatial metaphoric motion, temporal metaphoric motion, and three corresponding controls	Spatial motion, temporal motion	Visual	62	Spherical ROIs relevant to temporal and spatial processing, centered on coordinates from previous studies	Button press after catch trials (25%) indicating whether a probe word was related to the sentence
Citron and Goldberg (2014)	26	Metaphor, abstract	Taste	Visual	37	Anatomically defined gustatory areas based on WFU PickAtlas	Answer yes/no comprehension questions with a button press on occasional catch trials



Table 1 (continued)

Study	# subj	Conditions (sentences)	Domain	Presentation modality	# items per condition	Definition of ROIs	Task
Brain stimulation/lesion studies							
Cacciari et al. (2011)	8	Literal, metaphoric, fictive motion, and non-motion	Motion	Visual	27	Leg motor cortex localized with TMS	Passive reading, recognition test after
Reilly et al. (2019)	24	Literal, metaphoric, abstract	Action	Visual	12–14 per SOA	Hand motor cortex localized with TMS	Sensibility judgment with a left hand button press for each sentence
Fernandino et al. (2013)	20	Literal, metaphoric, idiomatic, abstract	Action	Visual	25	– (Parkinson's patients)	Sensibility judgment for each sentence
Johari et al. (2021)	23	Literal, metaphoric, idiomatic, visual	Action	Visual	20	HD-tDCS centered on hand motor cortex (group coordinates)	Sensibility judgment for each sentence

<sup>a</sup> Sixteen subjects were included in the study, but MT+ ROIs could be defined only for 13 subjects

study, showing activation in the left aIPL in a whole-brain analysis, with additional activation in the intraparietal sulcus and middle occipital gyrus (Fig. 1b). aIPL shows a linear trend, LIT > MET > IDI > ABS.

An additional finding in these two studies concerns the differences between the metaphoric and literal sentences. While metaphoric sentences were similar to the literal sentence in the aIPL, they activated an additional area in the mid superior temporal sulcus and middle temporal gyrus (mSTS/mMTG).<sup>4</sup> This area was also seen in the ABS > LIT, and can be considered a signature of abstract semantics (whatever its internal format may be). Thus, action metaphors showed similarities to both literal and abstract sentences, and were not identical to literal action sentences.

In an EEG study, Lai et al. (2019) examined the time-course of activation for action metaphors used in the Desai et al. (2011) study. They found that the frontal concreteness effect was similar for both LIT and MET sentences compared to ABS, with the same time-course. This suggests that action verbs in both metaphoric and literal contexts are interpreted similarly, as a concrete action. The MET > ABS comparison showed additional negativity in posterior electrodes, possibly reflecting additional resources recruited for metaphor interpretation. Thus, action metaphors showed both similarities and differences relative to literal action sentences.

Romero Lauro et al. (2013) found activation in a hand sentence ROI in the precentral gyrus for MET > ABS for upper limb action sentences. The same ROI also showed activation for upper limb LIT > ABS contrast.

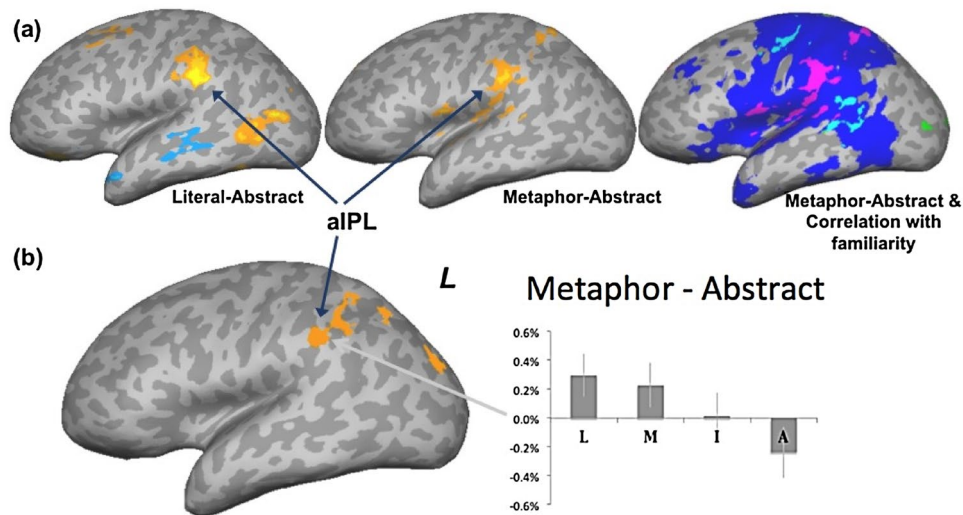
### Texture and body parts

Lacey et al. (2012) used texture metaphors such as *She had a rough day* and contrasted them with similar ABS<sup>5</sup> sentences (*She had a bad day*). In functionally defined texture-sensitive ROIs in left OP1, left OP3, and right OP1, greater activation for MET than ABS was found (Fig. 2a). While the small sample size ( $n=7$  subjects) is a reason to be cautious, the results are suggestive.

Lacey et al. (2017) used body part-specific metaphors (*He had to foot the bill*), LIT sentences with body parts (*His feet were small*), and corresponding control sentences without body part terms (ABS: *He had to pay the bill*; LIT-control:

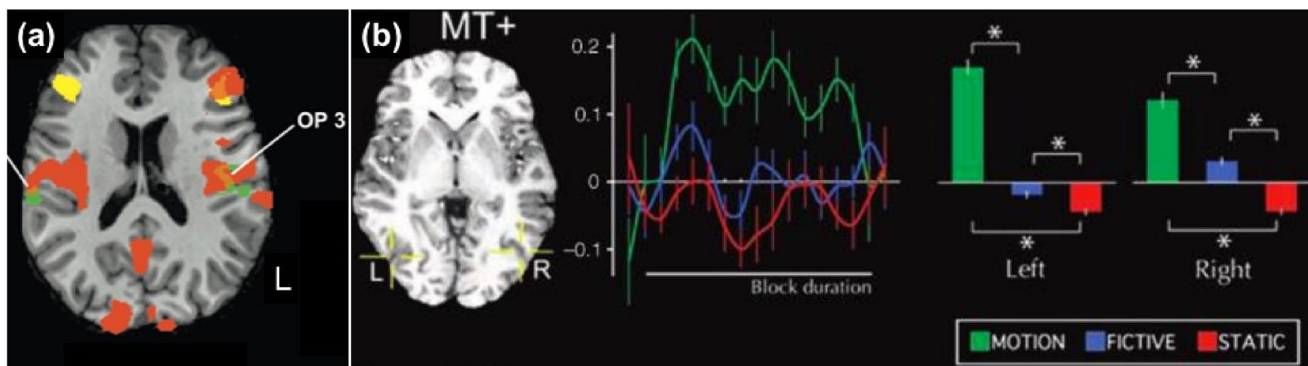
<sup>4</sup> This activation could be seen only due to the whole-brain analysis used in the study. If the analyses were targeted only to specific action ROIs, as is common, this area relevant to abstract semantics and with interesting theoretical implications would not be seen. This provides an example of the potential value of whole-brain analyses.

<sup>5</sup> They used the term 'literal' for this condition. Under the current nomenclature, such conditions are termed ABS.



**Fig. 1** **a** Activations from Desai et al. (2011) for literal and metaphor sentences (yellow-orange) compared to abstract (blue) sentences (left and central panel). In the rightmost panel, blue indicates activation from a motor localizer task, pink is action MET > ABS activation overlapping with the localizer, and cyan shows correlation with metaphor familiarity after factoring out abstract sentence familiar-

ity also overlapping with the localizer. **b** MET-ABS activation from Desai et al. (2013). Graph shows percentage signal change in the aIPL cluster for literal (L), metaphor (M), idiom (I), and abstract (A) conditions. Adapted from Desai et al. (2011) and Desai et al. (2013), respectively



**Fig. 2** **a** The main result from Lacey et al. (2012) study of texture metaphors. Orange—subject-specific haptic texture localizer; yellow—visual texture localizer; brown/green—textural metaphors and their overlap with haptic localizer in sensory area OP3 in the left hemisphere, in OP1 in the right hemisphere. **b** Results from Saygin

et al. (2010) study that used motion, fictive motion, and static sentences. Graphs show activations in individually localized area MT+. Adapted from Lacey et al. (2012) and Saygin et al. (2010), respectively

*His chair was small*). Metaphoric sentences had more words, and had lower naturalness, familiarity, and interpretability than the literal body part sentences, but still contained metaphors that had relatively high familiarity. Potential concerns related to time-on-task effects are alleviated by the fact that metaphor sentences had faster RTs than their control sentences. The interaction contrast (MET > ABS) > (LIT > LIT-control) activated a cluster in the left STG, and partly overlapped with extrastriate body area (EBA) identified in the visual localizer task. However, the motivation behind this contrast not clear, because one expects *both* metaphoric body

part and literal body part sentences to activate the EBA, and not one relative to the other. Contrasts MET > ABS and LIT > LIT-control were also examined separately, and overlap with limb-selective EBA for the former, but not the latter, was found. An additional interaction contrast, (limb metaphor > limb-control) > (face metaphor > face-control) also revealed activation in the EBA, showing that this activation is specific to limb metaphors, and is not a general characteristic of metaphor processing. The main puzzling aspect of the results is the question of why LIT sentences did not activate EBA. If metaphoric sentences are grounded

in visual areas that process body parts, surely literal body part sentences should also be grounded in this manner. At least two explanations can be offered. One, the metaphor control sentences were abstract, while the literal control sentences referred to physical actions and manipulable objects (*She scraped her plate; She closed her door; His chair was small*). These control sentences may also activate the EBA to some extent due to implied use of body parts, weakening the contrast LIT > LIT-control. Secondly, the small sample size ( $n = 12$  subjects) may have reduced power to detect effects.

## Motion

Saygin et al. (2010) used motion-related LIT sentences (*I drove from Modesto to Fresno*), FIC sentences (*The highway runs from Modesto to Fresno*) and static ABS sentences (*Modesto and Fresno are in California*). Motion-sensitive area MT+ localized in each subject using a separate localizer run. They found strong activation in both the left and right MT+ for LIT > ABS. They also found a small but significant activation for FIC > ABS in both of these regions, suggesting that metaphoric motion engages motion-related simulations (Fig. 2b). They observed a gradient, LIT > FIC > ABS, which is reminiscent of the gradient found in Desai et al., (2011) and (2013) studies in aIPL (LIT > MET > IDI > ABS) for action metaphors.

Chen et al. (2008) used motion predicate metaphors (MET: *The man fell under her spell*), literal motion (LIT: *The child fell under the slide*), and non-motive abstract sentences (ABS: *The merchant was greedy and gluttonous*). MET and LIT sentences were matched on a number of variables including concreteness, imageability, familiarity, naturalness, and plausibility. MET nouns had a higher written frequency than the other two types. The ABS sentences had lower concreteness and imageability, and greater naturalness and plausibility. Behaviorally, there was no difference in RT between the sentences, but METs were less accurate than the other two conditions. MET > ABS comparison reveal activation in pMTG. However, the LIT > ABS comparison did not show any activations for LIT, making the interpretation of pMTG as representing conceptual motion difficult. They suggest a posterior-to-anterior gradient of abstraction in motion processing, where literal sentences activate more posterior regions, and starting around MT+. Gradually more abstracted motion is processed as one moves along the lateral temporal lobe. A relatively small number of participants ( $n = 14$ ) might affect the results.

Wallentin et al. (2005a) used FIC and LIT motion sentences and compared them to static ABS sentences. Motion-related sentences together activated the pMTG compared to static sentences, and there were no differences among LIT and FIC sentences in this region. The critical FIC > ABS

contrast was not presented, but the FIC condition activated pMTG relative to meaningless control sentences containing nonwords. Another study by Wallentin et al. (2005b) used LIT, MET, and FIC sentences, but did not contain an ABS condition, and hence is difficult to evaluate.

Lai and Desai (2016) used spatial metaphors (fictive motion) (*The trail crawled until the end of the hills*) and literal motion sentences (*The caterpillar crawled towards the top of the tree*), with corresponding static sentences (*The trail faced the end of the hills; The caterpillar looked at the top of the tree*). This study also included temporal motion sentences, which will be discussed in the next section. Each sentence type was matched to its control on a number of psycholinguistic variables, and on rated comprehension difficulty. In ROIs defined by coordinates from previous studies, the spatial FIC sentences activated the pITG ROI anterior to area MT+, relative to its control sentences. The MT+ ROI did not show a difference in either fictive or literal motion sentences relative to their controls.

## Taste

Citron and Goldberg (2014) used taste metaphors (*She looked at him sweetly*) contrasted with ABS (*She looked at him kindly*), and found activation for metaphors in the left gustatory cortex (lateral orbitofrontal cortex, frontal operculum, and anterior insula). This activation was also found for single taste words compared to abstract words, making it unlikely that the activation reflects general metaphoric processing.

## Time

Lai and Desai (2016) used metaphors for temporal duration such as *Her seminar stretches across the afternoon*, with corresponding static control sentences (*Her seminar is in the afternoon*). Activation from these sentences was examined in specific locations identified in a meta-analysis of temporal perception studies (Wiener et al., 2010). Coordinates in the left anterior insula, IFG, and the right claustrum was upregulated for temporal metaphors relative to their static controls, but not for spatial metaphors or literal motion sentences relative to their controls. This suggests that portions of the temporal perception network may be used to process temporal motion.

## Brain stimulation studies

Cacciari et al. (2011) used LIT, MET, FIC, and IDI motion sentences compared with ABS sentences in a TMS study. TMS to the left primary leg area resulted in greater motor-evoked potentials for LIT, MET, and FIC sentences (but not IDI sentences) than ABS sentences.



Reilly et al. (2019) applied TMS at three time points (150, 300, 450 ms) after the onset of the verb in LIT, MET, and ABS sentences. With hand motor TMS at the 300 ms point, both LIT and MT sentences produced a significant slowing of RT compared to the control occipital TMS in the item analysis. Additionally, these two conditions also differed from ABS at 300 ms. (In the linear mixed effects analysis, the metaphoric condition produced a trending result at  $p < 0.053$ .)

HD-tDCS stimulation to hand motor cortex was used by Johari et al. (2021), who found interactions (MET, ABS)  $\times$  (real, sham stimulation) and (LIT, ABS)  $\times$  (real, sham) in RT in a meaningfulness judgment task. Their ABS condition used visual rather than abstract verbs. Both LIT and MET sentences were speeded up with the application of HD-tDCS relative to the visual control sentences, which is consistent with stimulation parameters that are known to induce excitation.

These studies suggest a causal or functional role of motor areas in processing action metaphors as well as literal action language.

## Negative results

In an fMRI study, Aziz-Zadeh et al. (2006) tested LIT and MET sentences. Action ROIs were defined by observation of actions. They found that LIT, but not MET sentences activated the action ROIs.

In Parkinson's patients and in age-matched controls, Fernandez et al. (2013) tested comprehension of LIT, MET, IDI, and ABS sentences using a meaningfulness judgment task. For the group (patients, controls)  $\times$  sentence type (MET, ABS) interaction, they did not find effects for response times. This interaction was significant for LIT and IDI sentences. In patients, there was a MET > ABS effect for RTs ( $p < 0.005$ ), while this difference was not significant in the control group. However, the critical RT interaction did not reach significance.

## Discussion

On a fairly consistent bases, sensory-motor metaphors activate corresponding sensory-motor areas. Action metaphors are the most commonly examined, but metaphors in other domains also show similar patterns. This result is supplemented by brain stimulation studies as well. While not all studies are ideal (for example, several use a small participant and/or stimulus set size, some do not report the critical MET > ABS contrast but rather discuss MET > LIT), there is sufficient consistency across studies to suggest that metaphors are grounded in sensory-motor system.

The negative result reported by Fernandez et al. (2013) is puzzling, given that in the same study, they found the

interaction for both LIT and IDI action sentence RTs. A possible explanation lies in the accuracy, where trending interaction was found ( $p < 0.08$ ) for metaphors. The MET accuracy was lower than ABS in patients, while it was higher in the control group. This can be a case of speed-accuracy tradeoff (Bogacz et al., 2010; Fernandez et al., 2018), where some of the increase in RT is absorbed by a reduction in accuracy.

On the other hand, for Aziz-Zadeh et al. (2006), two methodological factors may explain the negative result for MET. First is the low number of subjects in the study ( $n = 12$ ), which is about half of the recommended number and reduces the power. Second, there were only five different sentences per condition, which were repeated eight times each. Repetition suppression can play a role in reducing the magnitude of the BOLD response.

In case of motion metaphors, it is noteworthy that only one study found activation in the traditional motion perception complex MT+ (Saygin et al., 2010). The other three studies reported activation around this area, in pMTG or pITG. PMTG and pITG are indeed associated with action and motion, and hence the interpretation of this activation as motion-related can be justified. However, pMTG also has a more general role in sentence and verb frame processing. While these factors are presumably accounted for by the control sentences, there may be a lingering doubt whether this activation is truly specific to motion semantics. Importantly, only Saygin et al. (2010) used a subject-specific localizer task to identify MT+. They found significant individual variability in its location, as much as 10 mm on the anterior–posterior axis. This high variability may explain why the other three studies, which used a common anatomical location across subjects, failed to find activations in MT+, and highlights the importance of subject-specific localizers.

Some studies show in higher order sensory-motor cortex, such as aIPL, for metaphors and literal sentences. Some authors have argued that activation only in primary areas (such as M1 or V1) constitutes valid evidence for embodiment. Activation of higher order areas does not count, because these areas are multi-functional and modality nonspecific, and hence could represent some other processes. I disagree with this claim for multiple reasons. First, sensory-motor systems have been well studied and are known to extend well beyond primary regions. It is entirely possible for a process to have a visual component even if it occurs outside V1, and analogously for motor processes to occur outside M1 or auditory processes outside A1. For example, even in the macaque, corticospinal tracts receive only about 35% of the fibers from the primary motor cortex, and the rest of the input is from premotor, parietal, cingulate, and SMA regions (Galea & Darian-Smith, 1994). It is not possible to simply declare that these regions are not “real” motor areas, because they are (Rizzolatti & Luppino,

2001). A simplistic dichotomy between “modality specific” and “modality nonspecific” areas is mistaken.

The concern for potential confounds is legitimate, as indeed most if not all brain areas are multi-functional, depending on what is meant by “area” and “function.” That is why control conditions are included to account for nonspecific processes such as those related to phonology, orthography, attention, general sentence processing, executive processing, or task performance. Activation for a metaphoric sentence relative to a low-level baseline such rest or fixation could arise from myriad nonspecific processes. But if a control condition that accounts for such processes is included, then activations in higher order sensory-motor cortex can indeed be interpreted as evidence for embodiment. Many studies have taken great pains to carefully select stimulus materials for this reason. It is always possible that a confound was missed by the experimenters. However, the onus then is on the critic to (1) identify the specific confound, and (2) show that the confound could plausibly result in activation in the particular areas that were interpreted as reflecting sensory-motor processes. The best response is to conduct a study in which the putative confound is eliminated, and show that the purported sensory-motor activation disappears. It is not sufficient to simply state that activation in higher order sensory-motor areas could reflect any process and does not count. Functions of brain areas are not arbitrary, and their activation in neuroimaging studies is also not arbitrary. Much is known about many higher order areas, which can and should be used to interpret results. While reverse inference can indeed be used in an inappropriate manner (Poldrack, 2006), it is not inherently undesirable or a “bad thing,” and can also be used in a valid and informative manner. Several investigators have suggested that conceptual processing involves a hierarchy of areas ranging from primary to higher level sensory-motor areas, to multimodal and heteromodal areas such as angular gyrus (Fernandino et al., 2016; Kiefer & Harpaintner, 2020). Context and task demands determine the depth of activation at various levels of this hierarchy in a flexible manner.

While majority of the studies have examined action and motion metaphors, limited evidence exist for other domains as well, such as taste and time. Further examination of these other domains is clearly desirable. For example, a single study has examined temporal metaphors (Lai & Desai, 2016) that used coordinates from a meta-analysis of temporal perception studies to identify areas relevant to time processing. An obvious next step is to use temporal processing tasks as localizers at an individual subject level. Cross-linguistic studies, especially in languages that may use different metaphors than English (e.g., with a different direction of motion in space and time, or with different mappings between pitch and space), is another direction that would be of value.

## Metaphoric representation and abstraction

Jamrozik et al. (2016) propose that the metaphoric abstraction process has two characteristics: relational highlighting and sensory-motor shedding. Deeper relational meaning is highlighted, while superficial sensory-motor features are eliminated by the metaphor. For example, in the metaphor *Problems galloped into their marriage*, surface features such as four legs of a horse being off the ground are eliminated, while a deeper meaning is highlighted. Here, I present a partially different view. I propose that the intuitively appealing dichotomy between “deep” vs. “shallow,” or “core” vs. “surface” features of concepts, is mistaken. There is no essence of a concept, or a core, deep, or real meaning that is independent from the so-called surface features. They are inextricably intertwined so as to make this distinction fundamentally unsound. Metaphors highlight *which* sensory-motor features and relations are emphasized and can affect levels of detail, but never eliminate them altogether. Relational meaning is certainly important, but relations can exist only between entities. If they are between sensory-motor features, then they are sensory-motor relations. There is no core or deep meaning of *gallop* that is independent from the supposedly shallow features such as motion. Even additional details of speed and manner of motion are retained in the metaphor. If the metaphor is changed to *Problems seeped into their marriage*, the slow, gradual, and quiet manner of motion is highlighted. Even in an idiom such as *kick the bucket*, the quickness of motion is retained. Metaphors work by sensory-motor selection, and not by sensory-motor shedding.

Metaphors were found to have similarities to literal sentences in sensory-motor areas, but also to abstract sentences in the middle temporal lobe. Abstract concepts like *understand*, when expressed metaphorically as *grasp*, indeed have sensory-motor bases. However, the metaphoric *grasp* also has similarities to *understand* expressed literally. The mid-STS and anterior STG regions, activated by abstract concepts in single-word studies, and by abstract sentences, are also activated by action metaphors (the blue region in the left panel of Fig. 1a shows this activation, which is similar between ABS and MET conditions). This has implications for two models of metaphoric conceptual processing outlined by Murphy (1996). In the strong version, abstract concepts are defined entirely using the metaphors they are used in, and have no independent content. In the weak version, abstract concepts have basic independent representations, but are shaped by metaphoric usage (see also Gibbs, 1994a). The results above are more consistent with the weak version. The most common interpretation of temporal activation relates to phonology and phonological neighborhoods. A component of meaning could be represented by activating other concepts, and the temporal lobe system represents the

phonological access point to other concepts. This does not necessarily imply that this representation itself is abstract or symbolic. Abstract concepts themselves, and their neighbors accessed through phonology, could be grounded indirectly in sensory-motor systems, or in affective, interoceptive, and meta-cognitive systems (Borghetti et al., 2019; Desai et al., 2018). The results only show that action metaphors are not identical to literal sentences, and also have similarities to sentences with abstract meaning. A metaphor such as *theories are buildings* is used when someone suggest that a certain theory has a solid foundation. But people are still aware of differences between theories and buildings. It is possible that the concept of *theory* has an independent representation that is skeletal or impoverished, and is enhanced and enriched by frequent metaphoric alignment with buildings. This independent representation can be enhanced in different, even contradictory ways (e.g., by saying that a theory is *slippery* or *fluid*, which would not be possible for a building). On the other hand, concepts are likely dynamic and flexible, and need not have a fixed or static representation at all. The problem of multiple and contradictory metaphors can be handled by a view in which conceptual representations are created on the fly based on the context (Gibbs Jr., 1996). The question then is, what neural representation of *theory* is activated in a neutral context such as in *I like theories*? Experiments that can test whether such a representation is a “weighted average” of representations based on different metaphors for theories, or has an independent, non-metaphoric component, would be of value.

Theories are simultaneously more than buildings and less than buildings, and an appeal to additional metaphors is necessary if that is the only tool available. Furthermore, establishing appropriate connections between domains and discarding others seem to require prior understanding of the concepts. Abstract concepts appear to lack a prior structure that can be readily mapped to a concrete domain. The role of metaphoric mapping is precisely to provide that structure, but this assumes a pre-existing concept (presumably based on direct experience), which can be structured. From a developmental perspective too, many experiences come well before related words and metaphors are learned. Hence, while it is not obvious that metaphor can provide a complete solution to the problem of abstract concept representation (Barsalou & Wiemer-Hastings, 2005; Dove, 2009), it may certainly play a role.

## Idioms

Some of the behavioral and neuroimaging literature on metaphor processing commonly uses the terms ‘metaphor’ and ‘idiom’ interchangeably, and some consider idioms to be equivalent to conventional metaphors. For the purposes

of the current article, I distinguish between metaphors and idioms (sometimes called “dead metaphors”). An idiom is a string of constituents whose meaning is not necessarily derived from that of the constituents. Idiomatic meaning is retrieved from long-term memory. In an idiom such as *spill the beans*, both *spill* and *beans* are essential elements. *Drop the beans* or *spill the marbles* do not convey the same meaning. On the other hand, the metaphoric notion ‘grasping as understanding’ can be applied to many cases. Unlike idioms, metaphors—either novel or conventionalized—do not have a unique standardized meaning. A case such as *grasp the idea* is a familiar or conventional metaphor, but is not an idiom, because one can *grasp a theory*, *grasp the situation*, and so on. This productive nature of metaphors that allows for online combination of words distinguishes them from idioms.

Idioms are theoretically important due to their controversial nature in two aspects: metaphoricity and compositionality (Sanford, 2014; Vulchanova et al., 2019). Non-compositional models of idiom processing suggest that idioms are stored and retrieved as chunks of constructions, and function as a single lexical item (e.g., Gibbs, 1994b; Swinney & Cutler, 1979). Compositional models propose that idioms are analyzed compositionally at some level, and single words can have influence on its interpretation (e.g., Cacciari & Tabossi, 1988; Hamblin & Gibbs, 1999). Hybrid models that take elements of both proposals also exist (Titone & Connine, 1999). For our purposes, if the abstract meaning of an idiom is retrieved as a single lexical item, then it should not involve sensory-motor systems in the same way that metaphors do. If idioms are found to be grounded in sensory-motor systems, then compositional or hybrid accounts are supported. Idioms also vary in the degree of their decomposability or transparency, and this can affect the level of compositional analysis. Neuroimaging studies have not addressed this variable systematically, and hence we will not discuss it here but note it as a caveat.

## Positive findings

Boulenger et al. (2009) used arm- and leg-related IDI and LIT action sentences in an fMRI study. There was no ABS condition in this study, and the baseline only contained hash marks matched in length to the sentences. A differential effect for arm- and leg-related idioms was found in corresponding ROIs in the motor strip, showing semantic somatotopy, in a late analysis window that started from 3 s after the offset of the final critical word (*habit* in *Pablo kicked the habit*).

In a MEG study, arm- and leg-related idiomatic and literal sentences were used by Boulenger et al. (2012). In an analysis collapsing LIT and IDI sentences, significantly greater

activity was found in the arm ROI for arm sentences relative to the leg sentences. Activation of leg sentences in the leg ROI relative to that from arm sentence did not reach significance. In another analysis examining individual time points (as opposed to time 50-ms time windows used in the previous analysis), both arm and leg ROIs showed a body part  $\times$  ROI interaction.

In Parkinson's patients, Fernandino et al. (2013) found increased response times for literal and idiomatic action sentences relative to abstract sentences in an interaction with a control group (IDI, ABS)  $\times$  (patient, control).

Romero Lauro et al. (2013) found activation in a hand sentence ROI in the precentral gyrus for IDI > ABS for upper limb action sentences. The same ROI also showed activation for upper limb LIT > ABS and MET > ABS contrasts, supporting its role in action semantic processing.

Johari et al. (2021) applied HD-tDCS centered on the hand motor cortex and found interactions (IDI, ABS)  $\times$  (real, sham stimulation) and (LIT, ABS)  $\times$  (real, sham stimulation) in RT in a meaningfulness judgment task, with relative facilitation for IDI and LIT sentences.

## Negative findings

Raposo et al. (2009) used arm- and leg-related LIT and IDI sentences in an fMRI study. In the critical analysis, an interaction between arm/leg sentences and arm/leg ROIs was observed for LIT, but not for IDI sentences.

Cacciari et al. (2011) failed to find an effect on motor-evoked potentials (MEPs) for IDI > ABS with TMS to leg motor cortex, while finding this effect for LIT and MET sentences.

Desai et al. (2013) found no activation in motor areas such as aIPL for IDI sentences, while finding this activation for LIT and MET sentences relative to ABS.

## Discussion

Given the existence of several positive as well as negative results, the case of idioms warrants closer examination. Studies by Boulenger et al. (2009) and (2012) are among the best designed, due to the use of somatotopy. Rather than using an 'abstract' condition, where concepts may have indirect associations with actions, use of semantic somatotopy in these studies provides an ideal control, because actions are compared with other actions executed with a different effector. These studies also use individual localizer tasks rather than using group coordinates of other studies, which is another strength. They also have some limitations. For example, Boulenger et al. (2012) report only analyses that collapse literal and idiomatic sentences.

Stimulus materials used in some studies are also less-than-ideal. One issue is that the stimuli appear to be a mix of

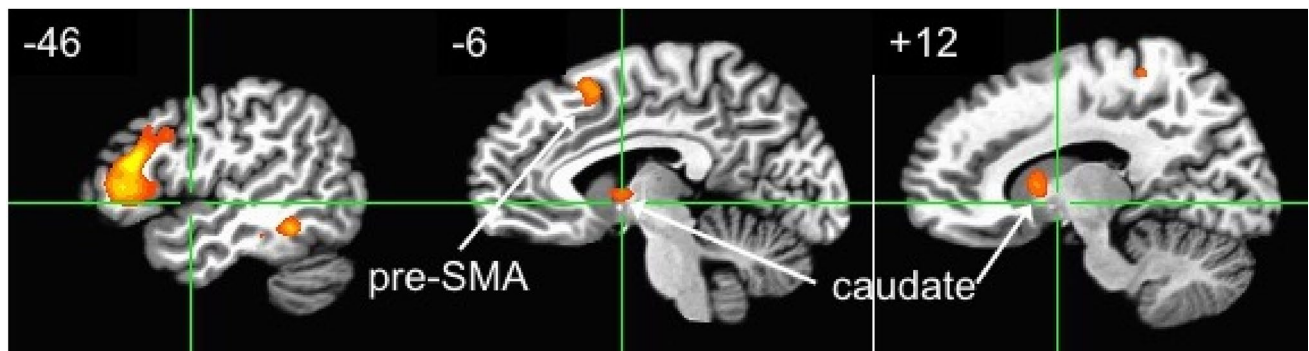
idioms and metaphors, rather than just idioms. For example, sentences such as *She caught the sun* and *He grasped the idea* are metaphors rather than idioms. A second issue is that some of the stimuli, while containing idioms, may not be processed as idioms due to a lack of context. For example, it is not clear that the sentence *John scraped the barrel* (Boulenger et al., 2012) fully activates an idiomatic meaning. (Contrast with *John could not find anyone qualified for this job and now he is scraping the barrel*, which is more likely to be understood in the intended idiomatic sense.) The isolated sentence could be processed more like a literal sentence if presented with minimal context. The general criticism of a lack of context to fully engage an idiomatic sense is applicable to all of the studies. In some studies, this problem is mitigated by changing the context in which action verb is encountered. Desai et al. (2013) and Fernandino et al. (2013) used inanimate agents in idiomatic sentences (The country lifted the veil on its nuclear program) and animate agents in literal sentences (The craftsman lifted the pebble from the ground). The context provided by the noun phrase makes literal interpretation of the action verb implausible for idioms. However, this is still limited context consisting of a single noun phrase. Studies that provide a more extensive context to clearly activate an idiomatic meaning (e.g., *The country was very secretive until it lifted the veil on its nuclear program*) would be valuable. Such stimuli create additional difficulties in matching conditions on psycholinguistic variables, which have to be addressed (e.g., by presenting a context sentence separately).

## Re-analysis of Desai et al. (2013) study

Given the inconsistency in results, I more closely examined results of the Desai et al. (2013) study that used IDI, MET, LIT, and ABS conditions. While studies typically examine only a few "motor areas," namely premotor cortex and aIPL, the motor system is extensive and partly hierarchical. Subcortical areas, especially the basal ganglia (BG), play a well-known role in action control. It is possible that action language, including idioms, engages the motor system, but at higher levels in the hierarchy. Some evidence are provided by Fernandino et al. (2013), who reported impairment of action idioms in Parkinson's patients, where subcortical motor circuits play a central role in action impairment.

Striatum and globus pallidus are central regions associated with action selection, planning, and modulation of ongoing action (Graybiel, 1998; Jin et al., 2014; Kim & Hikosaka, 2015; Markowitz et al., 2018). Within the striatum, lateral dorsal striatum/putamen is associated with rigid and automatic form of stimulus bound behavior that is less relevant to action here. In contrast, medial dorsal striatum/caudate is associated with flexible, goal-directed action, and contingencies between actions and consequences (Grahn





**Fig. 3** Activations in IDI > ABS contrast in data from Desai et al. (2013), at voxelwise  $p < 0.005$ . Frontal and pre-SMA activations are significant in whole-brain analysis, while the right caudate activation

is significant in an ROI analysis. Numbers indicate Talairach  $x$ -coordinates of the slice (negative is left hemisphere)

et al., 2008). Lehericy et al. (2006) found activation in caudate and anterior globus pallidus when comparing complex actions to simple actions (that included movements with and without simple temporal sequencing). Using peaks in right and left caudate ( $\pm 14, 10, 9$ ) and anterior globus pallidus ( $\pm 18, 2, 2$ ) from Lehericy et al. (2006), I defined spherical ROIs with 5 mm radius. Comparing action idiom to abstract sentences using  $t$  tests, results indicated significantly greater activation in the right caudate ( $p < 0.002$ ) and left caudate ( $p < 0.042$ ). Trends in the right and left anterior globus pallidus ( $p < 0.085$  and  $p < 0.065$ , respectively) were observed. The right caudate activation was also significant after corrections for multiple comparisons (Benjamini & Hochberg, 1995) (Fig. 3).

These results suggest a role of BG, and specifically caudate, in action idiom processing. Caudate has a role in facilitating appropriate motor programs or action schemas while inhibiting competing ones, and in selection of appropriate action sub-goals (Grahn et al., 2008; Jin et al., 2014), which may be used to ground action idioms. In addition to the well-known direct, indirect, and hyperdirect pathways, additional pathways between BG and cortex have been identified (for reviews, see Milardi et al., 2019; Haber, 2016). For example, a direct cortico-pallidal pathway projects mainly to sensorimotor regions, and has a likely role in sensorimotor integration (Cacciola et al., 2019). Projections between caudate and sensory-motor regions, including premotor cortex and pre-SMA, have a role in planning and learning sequential movements (Haber, 2016). Connectivity between BG and cerebellum is implicated in motor timing, and in movement disorders such as dystonia (Milardi et al., 2019).

The results suggest a role of BG and associated connections to sensory-motor cortical regions and cerebellum, in action idiom comprehension. A potential role of BG circuits in idiom comprehension is in action selection and planning. Action idioms may rely on selection of action schemas, but this activation may not fully percolate all the way to higher

order cortical areas associated with action execution, such as the aIPL. This grounding may be more automatic and low-level, whereby simulations weaken after action planning stage. It is interesting to note that pre-SMA was also activated for IDI > ABS contrast (significant after whole-brain correction), which is tightly connected to the basal ganglia, and also has a role in action selection and initiation (Akkal et al., 2007; Nachev et al., 2007, 2008). When stimulation is applied to cortical motor areas, as in Johari et al. (2021), it may percolate through motor circuits to the level of BG through cortico-BG loops, leading to modulation of idiom processing through cortical stimulation. While Johari et al. used a behavioral measure, Cacciari et al. (2011) used MEPs in their TMS study. If idioms are processed primarily at the level of action selection and action plans, this may reduce effects at the level of MEPs in muscles, potentially explaining the negative finding and the difference between the two stimulation studies.

A concern with this interpretation is that while BG have a well-established role in action control, they also have a more general role in executive function (Guo et al., 2018; Riva et al., 2018). Could the observed activation represent nonspecific processes related to general task demands or task difficulty? Two arguments can be presented against this possibility. First, idiom sentences in this study were carefully designed to have similar difficulty as abstract sentences. No difference in RT (in a meaningfulness judgment task) was found between IDI and ABS sentences, either in subject analysis or in item analysis. Secondly, MET sentences in this study also had similar (numerically higher, but statistically no-significant) RT to IDI sentences, and hence can be expected to have at least as much executive demands as the IDI condition. No activation in the ROIs was observed for MET > ABS contrast. This makes it unlikely that the activation here represents general sentence processing or decision-making processes, even for non-literal language.



Could the activation of BG represent an inhibition of action simulations rather than their planning, given that BG loops also play a role in action inhibition? This would imply that while LIT and MET sentences involve simulating actions at some level, comprehension of IDI involves the opposite process of action inhibition, and hence they are not grounded in the same manner. This is unlikely, given that brain stimulation results, such as those in Johari et al. (2021), result in identical effects for LIT and IDI sentences. If one type of sentence was understood through activating action simulations, while the other by inhibiting them, stimulation of motor cortex should result in opposite effects (facilitation in one case while interference in the other), which is not the case.

In sum, this result suggests a possibility that action idioms, due to their well-learned nature, are processed at the level of relatively abstract action schemas in BG and pre-SMA, while action metaphors are processed on-line in higher order motor cortex with relatively more detailed simulations. This may reconcile inconsistent positive and negative findings related to action idiom processing. This supports compositional and hybrid accounts of idiom processing that suggest some level of compositional analysis and influence of individual words in an idiom.

## Metaphoric organization without linguistic metaphors

The studies discussed above pertain to processing of linguistic metaphors. They show that when metaphoric language is processed, it is understood in terms of the source domain. CMT, however, suggests that there is a metaphoric relationship between abstract and concrete domains at the *conceptual* level, not just at the linguistic level. A mapping between concrete and abstract domains exist independently of language, and metaphors in language are a reflection of this underlying conceptual relationship. The fact that linguistic metaphors appear to be grounded in sensory-motor processing, as reviewed above, supports this view, but it is not sufficient to establish an underlying nonlinguistic relationship. Relationships between nonlinguistic domains of knowledge may not necessarily be reflected in linguistic metaphors (Casasanto, 2009), and vice versa. While there are behavioral evidence for such nonlinguistic relationship, at least in some circumstances (Casasanto & Bottini, 2014), neural evidence is very limited. Here, I describe three studies that speak to this question.

To examine whether visuospatial mechanisms may be used to process even isolated words, Quadflieg et al. (2011) used words associated with up/down location (airplane/carpet), positive/negative valence (beauty/accident), and high/low power (boss/assistant). Using a classifier that

was trained to classify the physical position of shapes, they showed that location and valence (but not power) can also be classified using the same classifier without further training, especially using the ROI of left IPS. This suggests that salient features of location and valence are grounded in spatial processes, even when they are not used explicitly in metaphors. A potential objection is that the IPS is multi-functional area, and in addition to spatial processing, is important to visual attention. These results could reflect differences in attentional demands or time-on-task differences between conditions, and not grounding in spatial processing per se. The fMRI task involved responses only on catch trials, and hence this possibility cannot be definitively ruled out. However, Quadflieg et al. compared response times and accuracy of their stimuli off-line, and found no differences between conditions, mitigating this concern.

Zanolie et al. (2012) examined the relationship between power difference in positions (e.g., boss vs. servant) and the vertical dimension of space, reflecting the conceptual metaphor *power is up*, in an ERP study. They found that congruent trials (high power associated with upper visual field) elicited a larger N1 than incongruent trials. The N1 can be interpreted as indexing a shift in spatial attention. This result is consistent with the notion that semantics of power are interpreted metaphorically through space, without presence of linguistic metaphors.

Tavares et al. (2015) used a social game to examine dimensions of power (e.g., dominance, hierarchy, and competence) and affiliation (e.g., intimacy, trustworthiness, and love). Just as power is associated with the vertical dimension of space, affiliation is frequently described as a horizontal dimension of space or distance and is reflected in linguistic metaphors (*She is very close to her niece; We are growing apart*). In the experiment, subjects developed relationships with other characters in the game by making voluntary choices in terms of power and affiliation, in absence of linguistic metaphors. They found that the hippocampus tracked the social coordinates defined by power and affiliation, when subjects “move” in this social space by making voluntary choices. Hippocampus is crucial for coding spatial and temporal context of events (Eichenbaum & Cohen, 2014). Absolute social distance was tracked by posterior cingulate, which is associated with spatial navigation. This suggests that abstract concepts of *power* and *affiliation*, and the resulting social relationship, may be represented in a spatiotemporal format even without any explicit use of linguistic metaphors.

## Conclusions

Abstract concepts can be understood by relating them metaphorically to concrete domains. Evidence from brain imaging, brain stimulation, and lesion studies, on balance, shows that when abstract concepts are expressed as linguistic metaphors to sensory-motor domains, they are understood in terms of those domains. Metaphors are embodied and grounded in sensory-motor domains. Such metaphors are understood not through a homonymous sense that is abstract (or as “unfortunate homonyms”), but through simulations in action-perception systems at varying levels of detail. Processing of these metaphors is not identical to that of literal concrete language, however, but also retains an abstract component. Abstract concepts may have independent representations that are shaped and enriched by metaphors dynamically.

The case of idioms is less clear, especially given that most studies have used limited to no context for encouraging idiomatic processing. Neuroimaging evidence suggest that at least, sensory-motor systems are not likely to be activated in the same way or to the same extent for idioms as they are for metaphors or for literal sentences. Based on preliminary evidence, I suggest that idioms may still be grounded, but in a qualitatively different manner than metaphors. They could be grounded through more schematic action planning, control, and goal circuits that sit higher in the action hierarchy in the basal ganglia.

Finally, there is neural evidence that some abstract concepts and relations, such as *power* and *affiliation*, have a metaphoric organization even in the absence of linguistic metaphors. Some components of the abstract conceptual system may indeed have underlying metaphoric bases, at least under certain conditions. Fleshing out the bounds of this organization—for example, the precise types of abstract concepts that are organized in this way, their flexibility, and the necessary conditions and context—awaits further investigation.

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## Declarations

**Conflict of interest** The author Rutvik H. Desai declares that he has no conflict of interest.

**Ethical approval** This article does not contain any studies with human participants or animals performed by any of the authors.

## References

- Akkal, D., Dum, R. P., & Strick, P. L. (2007). Supplementary motor area and presupplementary motor area: Targets of basal ganglia and cerebellar output. *Journal of Neuroscience*, *27*, 10659–10673.
- Aziz-Zadeh, L., Wilson, S. M., Rizzolatti, G., & Iacoboni, M. (2006). Congruent embodied representations for visually presented actions and linguistic phrases describing actions. *Current Biology*, *16*, 1818–1823.
- Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, *59*, 617–645.
- Barsalou, L. W., & Wiemer-Hastings, K. (2005). Situating abstract concepts. In D. Pecher & R. A. Zwaan (Eds.), *Grounding cognition: The role of perception and action in memory, language, and thought*. Cambridge University Press.
- Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of Royal Statistical Society B*, *57*, 298–300.
- Binkofski, F. C., Klann, J., & Caspers, S. (2016). On the neuroanatomy and functional role of the inferior parietal lobule and intraparietal sulcus. In G. Hickok & S. Small (Eds.), *Neurobiology of Language*. Academic Press.
- Bogacz, R., Wagenmakers, E. J., Forstmann, B. U., & Nieuwenhuis, S. (2010). The neural basis of the speed-accuracy tradeoff. *Trends in Neurosciences*, *33*, 10–16.
- Borghi, A. M., Barca, L., Binkofski, F., Castelfranchi, C., Pezzulo, G., & Tummolini, L. (2019). Words as social tools: Language, sociality and inner grounding in abstract concepts. *Physics of Life Reviews*, *29*, 120–153.
- Boulenger, V., Hauk, O., & Pulvermuller, F. (2009). Grasping ideas with the motor system: Semantic somatotopy in idiom comprehension. *Cerebral Cortex*, *19*, 1905–1914.
- Boulenger, V., Shtyrov, Y., & Pulvermuller, F. (2012). When do you grasp the idea? MEG evidence for instantaneous idiom understanding. *NeuroImage*, *59*, 3502–3513.
- Button, K. S., Ioannidis, J. P. A., Mokrysz, C., Nosek, B. A., Flint, J., Robinson, E. S. J., & Munafò, M. R. (2013). Power failure: why small sample size undermines the reliability of neuroscience. *Nature Reviews Neuroscience*, *14*, 365–376.
- Buxbaum, L. J., Johnson-Frey, S. H., & Bartlett-Williams, M. (2005). Deficient internal models for planning hand-object interactions in apraxia. *Neuropsychologia*, *43*, 917–929.
- Buxbaum, L. J., Kyle, K., Grossman, M., & Coslett, H. B. (2007). Left inferior parietal representations for skilled hand-object interactions: Evidence from stroke and corticobasal degeneration. *Cortex*, *43*, 411–423.
- Cacciari, C., Bolognini, N., Senna, I., Pellicciari, M. C., Miniussi, C., & Papagno, C. (2011). Literal, fictive and metaphorical motion sentences preserve the motion component of the verb: A TMS study. *Brain and Language*, *119*, 149–157.
- Cacciari, C., & Tabossi, P. (1988). The comprehension of idioms. *Journal of Memory and Language*, *27*, 668–683.
- Cacciola, A., Milardi, D., Bertino, S., Basile, G. A., Calamuneri, A., Chillemi, G., Rizzo, G., Anastasi, G., & Quartarone, A. (2019). Structural connectivity-based topography of the human globus pallidus: Implications for therapeutic targeting in movement disorders. *Movement Disorders*, *34*, 987–996.
- Casasanto, D. (2009). When is a linguistic metaphor a conceptual metaphor. In V. Evans & S. Pourcel (Eds.), *New directions in cognitive linguistics*. John Benjamins.
- Casasanto, D., & Bottini, R. (2014). Spatial language and abstract concepts. *Wiley Interdisciplinary Reviews: Cognitive Science*, *5*, 139–149.
- Casasanto, D., & Gijssels, T. (2015). What makes a metaphor an embodied metaphor? *Linguistics Vanguard*, *1*, 327–337.

- Chen, E., Widick, P., & Chatterjee, A. (2008). Functional-anatomical organization of predicate metaphor processing. *Brain and Language, 107*, 194–202.
- Citron, F. M., & Goldberg, A. E. (2014). Metaphorical sentences are more emotionally engaging than their literal counterparts. *Journal of Cognitive Neuroscience, 26*, 2585–2595.
- Cremers, H. R., Wager, T. D., & Yarkoni, T. (2017). The relation between statistical power and inference in fMRI. *PLoS ONE, 12*, e0184923.
- Desai, R. H., Binder, J. R., Conant, L. L., Mano, Q. R., & Seidenberg, M. S. (2011). The neural career of sensory-motor metaphors. *Journal of Cognitive Neuroscience, 23*, 2376–2386.
- Desai, R. H., Conant, L. L., Binder, J. R., Park, H., & Seidenberg, M. S. (2013). A piece of the action: Modulation of sensory-motor regions by action idioms and metaphors. *NeuroImage, 83*, 862–869.
- Desai, R. H., Reilly, M., & van Dam, W. (2018). The multifaceted abstract brain. *Philosophical Transactions of the Royal Society of London Series B Biological Sciences, 373*, 20170122.
- Desmond, J. E., & Glover, G. H. (2002). Estimating sample size in functional MRI (fMRI) neuroimaging studies: Statistical power analyses. *Journal of Neuroscience Methods, 118*, 115–128.
- Dove, G. (2009). Beyond perceptual symbols: A call for representational pluralism. *Cognition, 110*, 412–431.
- Eichenbaum, H., & Cohen, N. J. (2014). Can we reconcile the declarative memory and spatial navigation views on hippocampal function? *Neuron, 83*, 764–770.
- Fernandez, L., Huys, R., Issartel, J., Azulay, J. P., & Eusebio, A. (2018). Movement speed-accuracy trade-off in Parkinson's disease. *Frontiers in Neurology, 9*, 897.
- Fernandino, L., Binder, J. R., Desai, R. H., Pendl, S. L., Humphries, C. J., Gross, W. L., Conant, L. L., & Seidenberg, M. S. (2016). Concept representation reflects multimodal abstraction: A framework for embodied semantics. *Cerebral Cortex, 26*, 2018–2034.
- Fernandino, L., Conant, L. L., Binder, J. R., Blindauer, K., Hiner, B., Spangler, K., & Desai, R. H. (2013). "Where is the action? Action sentence processing in Parkinson's disease." *Neuropsychologia, 51*, 1510–1517.
- Galea, M. P., & Darian-Smith, I. (1994). Multiple corticospinal neuron populations in the macaque monkey are specified by their unique cortical origins, spinal terminations, and connections. *Cerebral Cortex, 4*, 166–194.
- Gibbs, R. W. (1994a). Figurative thought and figurative language. In M. A. Gernsbacher (Ed.), *Handbook of psycholinguistics*. Academic Press.
- Gibbs, R. W. (1994b). *The poetics of mind: Figurative thought, language, and understanding*. Cambridge University Press.
- Gibbs, R. W. (2011). Evaluating conceptual metaphor theory. *Discourse Processes, 48*, 529–562.
- Gibbs Jr, R. W. (1996). Why many concepts are metaphorical. *Cognition, 61*, 309–319.
- Goldenberg, G., & Karnath, H. O. (2006). The neural basis of imitation is body part specific. *Journal of Neuroscience, 26*, 6282–6287.
- Grahn, J. A., Parkinson, J. A., & Owen, A. M. (2008). The cognitive functions of the caudate nucleus. *Progress in Neurobiology, 86*, 141–155.
- Graybiel, A. M. (1998). The basal ganglia and chunking of action repertoires. *Neurobiology of Learning and Memory, 70*, 119–136.
- Guo, Y., Schmitz, T. W., Mur, M., Ferreira, C. S., & Anderson, M. C. (2018). A supramodal role of the basal ganglia in memory and motor inhibition: Meta-analytic evidence. *Neuropsychologia, 108*, 117–134.
- Haaland, K. Y., Harrington, D. L., & Knight, R. T. (2000). Neural representations of skilled movement. *Brain, 123*, 2306–2313.
- Haber, S. N. (2016). Corticostriatal circuitry. In D. W. Pfaff & N. Volkow (Eds.), *Neuroscience in the 21st century: From basic to clinical*. Springer.
- Hamblin, J. L., & Gibbs, R. W., Jr. (1999). Why you can't kick the bucket as you slowly die: Verbs in idiom comprehension. *Journal of Psycholinguistic Research, 28*, 25–39.
- Jamrozik, A., McQuire, M., Cardillo, E. R., & Chatterjee, A. (2016). Metaphor: Bridging embodiment to abstraction. *Psychonomic Bulletin and Review, 23*, 1080–1089.
- Jax, S. A., Buxbaum, L. J., & Moll, A. D. (2006). Deficits in movement planning and intrinsic coordinate control in ideomotor apraxia. *Journal of Cognitive Neuroscience, 18*, 2063–2076.
- Jin, X., Tecuapetla, F., & Costa, R. M. (2014). Basal ganglia subcircuits distinctively encode the parsing and concatenation of action sequences. *Nature Neuroscience, 17*, 423–430.
- Johari, K., Riccardi, N., Malyutina, S., Modi, M., & Desai, R. H. (2021). HD-tDCS over motor cortex facilitates figurative and literal action sentence processing. *Neuropsychologia, 159*, 107955.
- Johnson-Frey, S. H., Newman-Norlund, R., & Grafton, S. T. (2005). A distributed left hemisphere network active during planning of everyday tool use skills. *Cerebral Cortex, 15*, 681–695.
- Kiefer, M., & Harpaintner, M. (2020). Varieties of abstract concepts and their grounding in perception or action. *Open Psychology, 2*, 119–137.
- Kiefer, M., & Pulvermüller, F. (2012). Conceptual representations in mind and brain: Theoretical developments, current evidence and future directions. *Cortex, 48*, 805–825.
- Kim, H. F., & Hikosaka, O. (2015). Parallel basal ganglia circuits for voluntary and automatic behaviour to reach rewards. *Brain, 138*, 1776–1800.
- Kuhnke, P., Kiefer, M., & Hartwigsen, G. (2020). Task-dependent recruitment of modality-specific and multimodal regions during conceptual processing. *Cerebral Cortex, 30*, 3938–3959.
- Lacey, S., Stilla, R., Deshpande, G., Zhao, S., Stephens, C., McCormick, K., Kemmerer, D., & Sathian, K. (2017). Engagement of the left extrastriate body area during body-part metaphor comprehension. *Brain and Language, 166*, 1–18.
- Lacey, S., Stilla, R., & Sathian, K. (2012). Metaphorically feeling: Comprehending textural metaphors activates somatosensory cortex. *Brain and Language, 120*, 416–421.
- Lai, V. T., & Desai, R. H. (2016). The grounding of temporal metaphors. *Cortex, 76*, 43–50.
- Lai, V. T., Howerton, O., & Desai, R. H. (2019). Concrete processing of action metaphors: Evidence from ERP. *Brain Research, 1714*, 202–209.
- Lakoff, G. (1993). The contemporary theory of metaphor. In A. Ortony (Ed.), *Metaphor and thought*. Cambridge University Press.
- Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago.
- Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh: The embodied mind and its challenge to western thought*. Basic Books.
- Lauro, R., Leonor, J., Mattavelli, G., Papagno, C., & Tettamanti, M. (2013). She runs, the road runs, my mind runs, bad blood runs between us: Literal and figurative motion verbs: An fMRI study. *NeuroImage, 83C*, 361–371.
- Lehericy, S., Bardin, E., Tremblay, L., Van de Moortele, P. F., Pochon, J. B., Dormont, D., Kim, D. S., Yelnik, J., & Ugurbil, K. (2006). Motor control in basal ganglia circuits using fMRI and brain atlas approaches. *Cerebral Cortex, 16*, 149–161.
- Markowitz, J. E., Gillis, W. F., Beron, C. C., Neufeld, S. Q., Robertson, K., Bhagat, N. D., Peterson, R. E., Peterson, E., Hyun, M., Linderman, S. W., Sabatini, B. L., & Datta, S. R. (2018). The striatum organizes 3D behavior via moment-to-moment action selection. *Cell, 174*, 44 e17–58 e17.
- McGlone, M. S. (2007). What is the explanatory value of a conceptual metaphor? *Language and Communication, 27*, 109–126.

- McGlone, M. S. (2011). Hyperbole, homunculi, and hindsight bias: An alternative evaluation of conceptual metaphor theory. *Discourse Processes, 48*, 563–574.
- Milardi, D., Quartarone, A., Bramanti, A., Anastasi, G., Bertino, S., Basile, G. A., Buonasera, P., Pilone, G., Celeste, G., Rizzo, G., Bruschetta, D., & Cacciola, A. (2019). The cortico-basal ganglia-cerebellar network: Past, present and future perspectives. *Frontiers in Systems Neuroscience, 13*, 61.
- Murphy, G. L. (1996). On metaphoric representation. *Cognition, 60*, 173–204.
- Murphy, G. L. (1997). Reasons to doubt the present evidence for metaphoric representation. *Cognition, 62*, 99–108.
- Murphy, K., & Garavan, H. (2004). An empirical investigation into the number of subjects required for an event-related fMRI study. *NeuroImage, 22*, 879–885.
- Nachev, P., Kennard, C., & Husain, M. (2008). 'Functional role of the supplementary and pre-supplementary motor areas. *Nature Reviews Neuroscience, 9*, 856–869.
- Nachev, P., Wydell, H., O'Neill, K., Husain, M., & Kennard, C. (2007). The role of the pre-supplementary motor area in the control of action. *NeuroImage, 36*(Suppl 2), T155–T163.
- Orban, G. A., & Caruana, F. (2014). The neural basis of human tool use. *Frontiers in Psychology, 5*, 310.
- Pajula, J., & Tohka, J. (2016). How many is enough? Effect of sample size in inter-subject correlation analysis of fMRI. *Computational Intelligence and Neuroscience, 2016*, 2094601.
- Peeters, R. R., Rizzolatti, G., & Orban, G. A. (2013). Functional properties of the left parietal tool use region. *NeuroImage, 78*, 83–93.
- Poldrack, R. A. (2006). Can cognitive processes be inferred from neuroimaging data? *Trends in Cognitive Sciences, 10*, 59–63.
- Pollio, H. R. (1977). *Psychology and the poetics of growth: Figurative language in psychology, psychotherapy, and education* (L. Erlbaum Associates; distributed by the Halsted Press Division of J. Wiley: Hillsdale, N.J. New York)
- Quadflieg, S., Etzel, J. A., Gazzola, V., Keysers, C., Schubert, T. W., Waiter, G. D., & Macrae, C. N. (2011). Puddles, parties, and professors: Linking word categorization to neural patterns of visuospatial coding. *Journal of Cognitive Neuroscience, 23*, 2636–2649.
- Ramayya, A. G., Glasser, M. F., & Rilling, J. K. (2010). A DTI investigation of neural substrates supporting tool use. *Cerebral Cortex, 20*, 507–516.
- Randerath, J., Valyear, K. F., Philip, B. A., & Frey, S. H. (2017). Contributions of the parietal cortex to increased efficiency of planning-based action selection. *Neuropsychologia, 105*, 135–143.
- Raposo, A., Moss, H. E., Stamatakis, E. A., & Tyler, L. K. (2009). Modulation of motor and premotor cortices by actions, action words and action sentences. *Neuropsychologia, 47*, 388–396.
- Reilly, M., Howerton, O., & Desai, R. H. (2019). Time-course of motor involvement in literal and metaphoric action sentence processing: a TMS study. *Frontiers in Psychology, 10*, 371.
- Riva, D., Taddei, M., & Bulgheroni, S. (2018). The neuropsychology of basal ganglia. *European Journal of Paediatric Neurology, 22*, 321–326.
- Rizzolatti, G., & Luppino, G. (2001). The cortical motor system. *Neuron, 31*, 889–901.
- Sanford, D. (2014). Idiom as the intersection of conceptual and syntactic schemas. *Language and Cognition, 6*, 492–509.
- Saygin, A. P., McCullough, S., Alac, M., & Emmorey, K. (2010). Modulation of BOLD response in motion-sensitive lateral temporal cortex by real and fictive motion sentences. *Journal of Cognitive Neuroscience, 22*, 2480–2490.
- Swinney, D., & Cutler, A. (1979). The access and processing of idiomatic expressions. *Journal of Verbal Learning and Verbal Behavior, 18*, 523–534.
- Tavares, R. M., Mendelsohn, A., Grossman, Y., Williams, C. H., Shapiro, M., Trope, Y., & Schiller, D. (2015). A map for social navigation in the human brain. *Neuron, 87*, 231–243.
- Titone, D. A., & Connine, C. M. (1999). On the compositional and noncompositional nature of idiomatic expressions. *Journal of Pragmatics, 31*, 1655–1674.
- Tunik, E., Frey, S. H., & Grafton, S. T. (2005). Virtual lesions of the anterior intraparietal area disrupt goal-dependent on-line adjustments of grasp. *Nature Neuroscience, 8*, 505–511.
- Tunik, E., Lo, O. Y., & Adamovich, S. V. (2008). Transcranial magnetic stimulation to the frontal operculum and supramarginal gyrus disrupts planning of outcome-based hand-object interactions. *Journal of Neuroscience, 28*, 14422–14427.
- Turner, B. O., Paul, E. J., Miller, M. B., & Barbey, A. K. (2018). Small sample sizes reduce the replicability of task-based fMRI studies. *Commun Biol, 1*, 62.
- Varney, N. R., & Damasio, H. (1987). Locus of lesion in impaired pantomime recognition. *Cortex, 23*, 699–703.
- Villani, C., Lugli, L., Liuzza, M. T., & Borghi, A. M. (2019). Varieties of abstract concepts and their multiple dimensions. *Language and Cognition, 11*, 403–430.
- Vingerhoets, G. (2014). Contribution of the posterior parietal cortex in reaching, grasping, and using objects and tools. *Frontiers in Psychology, 5*, 151.
- Vulchanova, M., Milburn, E., Vulchanov, V., & Baggio, G. (2019). Boon or burden? The role of compositional meaning in figurative language processing and acquisition. *Journal of Logic, Language and Information, 28*, 359–387.
- Wallentin, M., Lund, T. E., Østergaard, S., Østergaard, L., & Roepstorff, A. (2005a). Motion verb sentences activate left posterior middle temporal cortex despite static context. *NeuroReport, 16*, 649–652.
- Wallentin, M., Østergaard, S., Lund, T. E., Østergaard, L., & Roepstorff, A. (2005b). Concrete spatial language: See what I mean? *Brain and Language, 92*, 221–233.
- Wang, J., Conder, J. A., Blitzer, D. N., & Shinkareva, S. V. (2010). Neural representation of abstract and concrete concepts: A meta-analysis of neuroimaging studies. *Human Brain Mapping, 31*, 1459–1468.
- Wiener, M., Turkeltaub, P., & Coslett, H. B. (2010). The image of time: A voxel-wise meta-analysis. *NeuroImage, 49*, 1728–1740.
- Zanolie, K., Dantzig, S. V., Boot, I., Wijnen, J., Schubert, T. W., Giessner, S. R., & Pecher, D. (2012). Mighty metaphors: behavioral and ERP evidence that power shifts attention on a vertical dimension. *Brain and Cognition, 78*, 50–58.