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What is up and down in embodied language processing? An experimental study on semantic priming of visual perception

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Abstract:

Linguistic processing has been suggested to involve rich perceptual representations grounded in non-linguistic experiential content often straddling multiple modal cognitive systems. This distributed approach implies that the processing of words signifying perceptual content can interfere with other aspects of perceptual experience through cross-modal priming. In an experimental study, we investigated semantically activated cross-modal priming between perception of auditory verbs and visual motion illusions. Participants solved a lexical decision task involving concrete and abstract verbs while presented with the Motion Quartet Paradigm, a visual stimulus inducing the illusory experience of vertical or horizontal motion. We found that the semantic direction of verbs primed participants to experience the visual stimulus as moving in compatible directions (horizontally or vertically), supporting our predictions. Interestingly, and contrary to our hypotheses, the priming effect was mainly driven by abstract words. We suggest that these results might be due to the socially interactive semantics of the abstract words.

Keywords: semantic priming, dynamical systems, lexical decision, abstract verbs, concrete verbs

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1 Introduction

It has recurrently been suggested that language-processing may give rise to rich perceptual representations. This implies that the processing of words and sentences relies on a distributed set of *modal* representation not specific to language. For example, semantic processing of concepts referring to movement or action are found to activate non-linguistic motor representations (Hauk et al. 2004; Klatzky et al. 1989; Tettamanti et al. 2005; Wallentin et al. 2011), while the comprehension of spatial language seems to activate domain general systems for spatial navigation (Wallentin et al. 2005, Wallentin et al. 2006). Conceptual Metaphor Theory (Lakoff and Johnson 2008) proposes that language reflects a set of underlying structural properties deriving from phenomenological embodied experiences with the world. Such structural properties could be basic experiences of spatial, causal, and relational regularities of the physical surroundings, such as orientation, depth, movement, or event structure, which over time generalize to basic schematic representations or *image schemas* (Johnson 1989). A celebrated example is that of the ‘containment’ schema which, for instance, is activated by the preposition ‘in.’ The expression “Chuck is in love” thus conceptualizes love as a container and Chuck’s feeling as one of being contained *in the state of love*. Importantly, the containment-schema is thought to apply to concrete experiences (seeing water in a glass) as well as abstract experiences (being in love) and thus the same conceptual structure can be common to various aspects of experience (Lakoff and Johnson 1980, Lakoff and Johnson 2008, and Lakoff and Johnson 1999).

As a consequence of the embodied grounding of conceptual structure, semantic processing may potentially activate multiple modalities within the whole body. Related to embodiment and metaphor theory is the concept of *perceptual simulations* (Barsalou 1999), which holds that perceptual information activated during a given experience can become integral to the representation and thus reactivate when linguistically reevoking the experience at a later point. Multimodal cognitive processing can cause perceptual information from different modalities to interact in various ways. This has been illustrated in studies addressing cross-modal processing, where one sense appears to alter and interfere with another. For example, when multiple auditory tones were accompanying a visual presentation of a single white flash on a screen, it resulted in the illusory perception of

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multiple white flashes (Shams et al. 2000). The finding suggest that our cognitive system anticipates interdependencies between different aspects of perceptual experiences even if these straddle modalities, giving rise to interesting interactions between bottom-up and top-down aspects of processing. If comprehending a sentence activates a mental simulation, this might come to interact with the perceived reality by top-down influencing low-level perceptual processes (Meteyard et al. 2007; Zwaan et al. 2004). In this context, we define “top-down” processes as feed-forward predictions informed by prior experience and “higher order” cognitive processes like language (for a critical discussion, see Firestone and Scholl 2016). As an effect of top-down cross-modal interaction, one visual interpretation can become actualized in favor of another through semantic priming. For example, in a EEG study, Boutonnet and Lupyan (2015) showed that visual object-recognition was faster when participants listened to a category label, such as ‘dog,’ than when they heard a lower-level auditory stimulus, of a sound of a dog barking.

1.1 Abstract and concrete motion

Motion-verbs may activate perceptual simulations that include direction of motion. This seems trivial for concrete verbs such as *run* or *climb*. Dils and Boroditsky thus found that processing motion-language influences mental imagery for compatible motion-directions (2010b) and that processing literal and metaphorical motion-language influences the perception of ambiguous visual stimuli, with literal motion being more influential (2010a). However, it has been argued that the spatial character of linguistic semantics is also characteristic for abstract verbs, such as *respect*, *succeed*, or *hope* (Lakoff & Johnson 2008; Richardson et al. 2001). According to CMT, this is due to the image-schematic structuring of abstract concepts: Our comprehension of abstract concepts is thus mediated by mapping conceptual structure from more concrete and perceivable domains of meaning. For instance, we often talk about time using spatial metaphors such as *on the other side of the weekend* or *let’s leave this behind*, conceptualizing the abstract domain of time by means of a spatial organization of events. This kind of structure-mapping from concrete sensory-perception to abstract concepts makes the meaning of abstract concepts more accessible (Lakoff and Johnson 2008). The image schematic nature of concepts was investigated in a study by Richardson et al. (2001), in which they tested participants’ spatial associations about the semantics of verbs presented on a scale from low to high ‘concreteness.’ They found that participants generally agreed about the spatial schematics associated with abstract as well as concrete verbs. For example, Richardson et al. (2001) demonstrated that participants largely agreed that the abstract word *respect* was semantically associated with a conceptual structure of verticality.

The processing of concrete versus abstract concepts is a debated subject and the field is dominated by several theories. Some assumptions hold that the processing of concrete and abstract concepts differ in terms of the degree to which a concept is imaginable, directly perceivable through the senses, acquired through the language system or connected to emotional processing and introspection (Barsalou & Wiemer-Hastings 2005; Scorolli et al. 2011; West & Holcomb 2000). Following this approach, the processing of abstract concepts is more dependent on their relations to other words while concrete concepts are more accessible to direct sensory perception. The dual coding theory (Paivio 1990, Paivio 1991) and the context availability theory (Bransford & McCarrell 1974; Kieras 1978) both propose an advantage for processing and retrieving concrete words, but for different reasons: while dual coding theory holds that the concrete-abstract distinction is determined by how perceptually available a concept is, the context availability theory suggests concreteness to be a function of how easily relevant contextual information for word-representation comes to mind. Yet emotion-words are often rated to be abstract despite being instantiated as physical activity in the body and therefore perceptually accessible (Wiemer-Hastings et al. 2001). Barsalou and Wiemer-Hastings (2005) proposed that abstract words are not represented in an amodal code, but are rather also perceptually simulated, although the context and situations that constrain their meanings are of a more varied, complex, and open character than what is the case for concrete words. They found that some of the relevant elements required for representing concrete concepts were objects, locations, and behavior (e. g. representing “chair” includes its use and frequent location as contextual information), while the elements in focus for representing abstract concepts are the social aspects of a situation and its introspective judgments (e.g. “respect” is represented by a more varied type of information, but experiencing it does not exclude perceptual activity, Barsalou and Wiemer-Hastings 2005). In this way, sensory-system processing may not be reserved for concrete concept-comprehension alone, but rather is involved in the processing of both concrete and abstract concepts, although perhaps in a more indirect way in the case of abstract concepts.

1.2 The dynamic nature of human cognition

A central assumption guiding this study is that human cognition is best described as structured along the principles of dynamical systems (Gibbs & Cameron 2008; Kelso 1995; Spivey 2008). That is, cognitive processes (e. g. related to linguistic material) unfolds as a probabilistic dynamic process sometimes depicted as a movement through a landscape of multiple attractor states which are continuously updated in terms of their relative strength of attraction. When asked if the animal *whale* belong to the category *mammal* or *fish*, we might for a brief second be attracted to *fish*, before finally answering *mammal*, due to the visual and contextual similarities between whales and fish. The conflict of attraction to multiple options during processing has for instance been illustrated in studies using mouse tracking (Farmer et al. 2007; Spivey et al. 2005). From the dynamical systems theoretical framework come three central concepts that will be particularly important for this study: *stability*, *instability*, and *phase shifts* (Kelso 1995). *Stability* describes a relatively and momentarily stable and ordered state of a system at a given point in time (ibid.). When some parameters change, it creates events in the system that cause instabilities to occur (for instance due to changes in the relative strength of attractors). It is during these instabilities that *phase shifts* (or phase transitions) are especially likely to occur. A phase shift is a shift to another and qualitatively different state of the system (ibid.).

The motion quartet paradigm (MQP) (Hock et al. 1993) is an experimental design inducing a visual illusion of apparent motion while allowing tight control over relevant parameters (Ploeger et al. 2002). The design is based on insights from dynamical systems theory and thus well suited for estimating the degree to which semantic processing can shift the relative attraction of visual interpretations – that is, induce cross modal priming. The paradigm has two dots presented diagonally, shifting places at quick succession, which creates the illusion of the dots moving between these positions. The apparent motion may be perceived as either vertical or horizontal (see Figure 1). The visual perception of direction depends on the *aspect ratio* – that is, the relative distances of height to width between the dots. Figure 1 illustrates that when the aspect ratio is manipulated gradually, it can shift the relative attraction to one of the two apparent directions: When the flickering dots produce a small and broad “rectangle,” it elicits a perception of vertical motion-direction. When the rectangle instead is tall and slim, it results in an impression of horizontal motion-direction. The vertical and horizontal motion-directions represents extremes on a continuum and *stable states* of a dynamical system (Kelso 1995; Ploeger et al. 2002). For the present purpose, the term *step-value* indicates the aspect ratio of distances between the dots. The step-value spans from 0 to 14, and each step represents a gradual change in the visual configuration. In other words, it is a control parameter, making it possible to measure at what point the experience of an observer *shifts* between the vertical and horizontal motion-perception. At step-value 7, the vertical and horizontal motion-perceptions are, in principle, simultaneously available (however, individual perceptual biases can push the maximal unstable point a step or two in either direction). When two stable visual perceptions are coexisting and equally likely to be experienced, the visual perception becomes ‘multistable’ (i. e. unstable), and the probability of visual phase shifts increases (Hock et al. 1993; Kelso 1995).

Figure 1: Example of the step-values that indicate three of the aspect ratios in the motion quartet. The arrows and non-filled circles were not part of the visual stimulus but added for illustration of the experience. The non-filled circles indicate the position of the non-activated flickering dot. The arrows illustrate the apparent (illusory) motion induced by the flicker. For small step-values (~ 0–4, Figure 1a), the perception of a vertical motion-direction is dominant. At the middle step-values (~ 5–9, Figure 1b), both motion-directions are equally likely to be perceived, which makes these step-values multistable. For large step-values (~ 10–14, Figure 1c), a horizontal motion-direction is likely to be perceived.

One advantage of the MQP is that it allows us to observe and elicit visual phase shifts and thus to investigate if impressions in a different modality (a semantic prime) can affect the threshold of the phase shift. It is likely that participants will be maximally susceptible to the influence of semantic priming of the visual decision at the maximally unstable point. By carefully staircasing each individual to her maximally unstable parameter setting, it is possible to test whether priming with spoken words influences visual perception of either horizontal or vertical motion.

In order to test our experimental hypotheses, we combine the MQP with a lexical decision task (Meyer and Schvaneveldt 1971). A lexical decision task is a word-comprehension task in which participants are randomly presented with real words and pseudo-words one-by-one and have to decide if the word they just heard was

a real word or a pseudo-word. Pseudo-words sound like words but have no lexical meaning (for example, “choof”). In order to solve the lexical decision, it is argued that participants need to do semantic processing, that is, (attempt to) access the semantics of the word. In this context, the lexical decision task is thus used to ensure that participants are listening to stimulus words before they are presented to the visual stimuli (MQP), since they know they will subsequently be asked to make a lexical decision. The procedure allows us to test if semantic processing of concrete and abstract words affect our interpretation of the visual stimulus. In summary, we hypothesize that:

H1: Participants' experience of perceived direction of motion will depend on the control parameter of step value, with small values inducing the experience of vertical motion while high numbers will induce the experience of horizontal motion. This is tested in the staircase phase of the experiment.

H2: Participants' responses will show maximal instability of their perceptual decision as the control parameter gets closer to the central step values indicating that the human visual system follows the principles of dynamical systems.

H3: When perceiving maximally instable MQP stimuli, priming participants with words associated with horizontal or vertical motion semantics will affect their perception of the stimuli to experience the illusion as horizontal or vertical respectively.

H4: The priming effect will be stronger for concrete motion words than for abstract (inferred/metaphorical) motion words.

The hypothesis-testing part of the analysis is followed up by an exploratory analysis controlling for effects of word frequency and a number of semantic dimensions of the lexical stimuli.

2 Materials and methods

2.1 Participants

21 participants (10 female, 10 male, 1 other, mean age = 34.4, SD = 15.5) took part in the experiment. 12 of the participants were students at Aarhus University. The remaining were acquaintances, friends, or family members of the first author.¹ All participants signed informed consent before participating in the experiment following local research ethics guidelines. Twenty of the participants were native Danish speakers, while one was a native Icelandic speaker proficient in Danish.

2.2 Materials

The experiment was programmed and run in the experimental software PsychoPy2, version 1.85.4 (Peirce & MacAskill 2018; Peirce 2007). Most participants were tested on an ordinary 22-inch screen PC running Windows 10 with a viewing distance of approximately 50–60 cm. The auditory stimuli were presented using standard on-ear headphones carefully adjusted in volume prior to experiment start. The remaining participants were tested using a MacBook Pro Retina 13-inch 2013 laptop with a viewing distance of approximately 40–50 cm, also using on-ear headphones adjusted to designated volume settings. In all cases, participants responded using the 'v' (vertical), 'h' (horizontal) and 'n' (neutral) keys on their respective keyboards. Word and non-word auditory stimuli were recorded by the first author using a Zoom H2n Handy Recorder and edited using the free audio software Audacity, version 2.0.6 (www.audacityteam.org). A post-experiment debriefing survey was created and presented using Google Forms.

2.3 Stimuli and procedure

The motion quartet stimuli were presented as white circular dots against a dark grey background and consisted of 14 different aspect ratios (the relative distance between dots). A fixation cross in the middle of the motion quartet was kept constant during each trial. The dots flickered at a rate of 150 milliseconds.

In the initial staircasing phase, a visual trial lasted for 5 seconds. The 14 aspect ratios each appeared 4 times. After each trial, participants were prompted to respond by a text on the saying: “horizontal (h) or vertical

(v)?” Participants responded by typing one of the designated letters on the keyboard. Furthermore, they were informed, that they could give a neutral response by pressing ‘n’ (neutral) if they believed they saw none of the directions – however, this option was not printed on the screen. The initial staircasing-part consisted of 56 trials, after which a notification was shown on screen asking participants to wait for the experimenter for further instructions. The experimenter then assessed a plot of the staircasing data expressing the individual participant’s probability of perceiving horizontal or vertical motion as a function of the 14 step values. The experimenter identified the step-value closest to a 0.5 probability, reflecting the step value giving rise to the maximally instable perception of direction for the individual participant. This was often found in the step-values approximating the middle at step 5–9. In case participants gave equally unstable responses to multiple steps, say 7 and 8, we chose the one closer to seven (the objectively more ambiguous step value). This value was inserted back in the experimental paradigm as the parameters setting of MQP for the remaining part of the experiment (see Figure 2 and Figure 3).

2.3.1 Staircasing procedure

Figure 2: Timeline for a single staircase trial. Notice that on the first screen, blank dots and arrows are added for illustration of the experience of apparent motion and was not part of the actual display.

Figure 3: Example of a plot of maximum instability, presented subsequent to the staircase session. This plot indicates a maximum unstable state at step value 5.

2.3.2 Experimental procedure

In the following experimental session, the same MQP stimuli were used, together with auditory word stimuli and a lexical decision task. Each trial started with an auditory word stimulus. Immediately after, the visual MQP stimuli appeared. The trial ended with two response requests: First, the participant was asked to indicate the perceived direction of the visual stimuli (like in the staircasing session described above). Second, the participant was asked to indicate if the word was a real or a pseudo word by pressing the keys ‘w’ (for *word*) or ‘r’ (for *pseudo*).

word) (see Figure 4). The auditory stimuli consisted of 30 verbs and 17 pseudo-words. Verbs were adopted from a comprehensive verb-direction norming study by Richardson et al. (2001). The original list used by Richardson and colleagues was taken from the concreteness dictionary of the MRC Psycholinguistic database (Coltheart 1981) that provides verb-ratings from low to high concreteness. For their study, Richardson et al. divided words in two groups of low (abstract) and high concreteness and our study rely on the same binary categorization. Pseudo-words were selected from a list available in Bangert et al. (2012). The 30 test-verbs were divided into three conditions: 10 concrete verbs, 10 abstract verbs and 10 neutral verbs. The 10 concrete and 10 abstract words each consisted of 5 horizontally directed and 5 vertically directed verbs (following Richardson et al.'s norms). The condition with neutral filler words was divided in 5 neutral-abstract verbs and 5 neutral-concrete verbs. The word order was randomized and each word was played two times. Filler and pseudo-words could appear with any aspect ratio of the MQP stimuli, while the critical test-words (abstract and concrete) would only appear together with the (individually staircased) maximally instable step value. Each auditory stimulus lasted ~ 2 seconds.

Figure 4: The timeline for a single trial in the main experimental session.

Most participants were tested in a university campus computer room. The remaining participants were tested at different sites such as private living-rooms and a studio-atelier. In all cases it was ensured that participants were not distracted by noise or activities in their near vicinity. Prior to the experiment start, participants received both oral instruction and written instructions in Danish and printed on screen in English. Experimenters were present in the room to answer questions and to assist participants' transition between the staircase session and the main experimental session.

Participants were instructed to respond to the stimuli in a way that reflected their visual impression of the stimuli. Apart from considering the lexical decision, there was no explicit success criteria and no feedback was provided. The experiment was self-paced and participants could spend the time they needed to respond. The entire experimental session including instructions lasted approximately 20 minutes and did not exceed 30 minutes.

The study also included a debriefing questionnaire, examining the participants' intuitions about the directionality of the test-verbs. This had a double purpose: rather than using the general norming of verb directionality from Richardson et al. (2001), we could use participants' own individual verb-association to predict how they comprehended the verbs and thus whether the associated direction would affect vision. Secondly, based on the participant verb-norms, we could construct a direction-predictor that included the finer gradations of verb-directionality, lying on a continuum between vertical and horizontal directions. This allowed to test more sophisticated predictions concerning the priming of visual experience. The post-experiment questionnaire was sent to the participants on email and included the 30 test-verbs. One word was presented at a time, together with 3 response options: vertical, horizontal, or neutral. Participants were requested to categorize the verbs in accordance with their immediate associations of verb-direction. Only 12/21 participants filled in the form; however, it still allowed us to collect a general estimate of verb-direction from the target participant population. The test words and their ratings are presented in Table 4 in the appendix.

2.4 Analysis

Through all analyses, we applied a linear mixed effects modelling approach using the packages lme4 (Bates et al. 2015) and lmerTest (Kuznetsova et al. 2017) in the statistical environment RStudio (RStudio Team 2015). All models are fitted by maximum likelihood (Laplace Approximation).

In response to hypothesis 1, we used a mixed effects logistic regression. As outcome we included the binary response (vertical vs. horizontal) while step value was the ordinal fixed effect. ID of participant was added as random intercept and step value as random slope per participant.

$$\text{response} \sim \text{step value} + (1 + \text{step value} \mid \text{participant ID})$$

To test hypothesis 2, we first created an index of response variability (how much the participant varied in response to the same step value) by summarizing the standard deviation of responses across repetitions of the staircase stimuli. We then created a linear mixed effect model with the variability of response as outcome variable and step value as ordinal fixed effect. Again, participant ID was added as random intercept.

$$\text{response variability} \sim \text{step value} + (1 \mid \text{participant ID})$$

To test hypotheses 3 and 4, we first inspected participants' classification of words as signifying horizontal and vertical directionality from the post-experiment survey. Intercoder reliability across all items was "fair" (Fleiss' Kappa = 0.28, Landis and Koch 1977), however, substantially higher for concrete verbs (K = 0.36) compared to abstract verbs (K = 0.17). These observations suggest that verb semantics can be ambiguous with respect to directionality, especially in the case of abstract verbs, and that this variable is better treated as a continuum (i. e. an expression of more or less attraction to vertical or horizontal movement) than a binary either-or variable. We therefore constructed a predictor variable from participants' debriefing responses with averaged directionality scores for each item between -1 (vertical) and 1 (horizontal). For instance, "lift" was judged by all participants have vertical directionality (and thus got a -1), while "argue" got more mixed ratings and thus got a score of 0.2 suggesting a more subtle attraction towards horizontal movement (see Table 1 for averaged directionality scores).

Table 1: Averaged directionality scores (vertical: -1/horizontal: 1) derived from participants' debriefing ratings of concrete and abstract target concepts.

Concrete									
<i>lift</i>	<i>climb</i>	<i>grow</i>	<i>sink</i>	<i>bomb</i>	<i>walk</i>	<i>point</i>	<i>push</i>	<i>flee</i>	<i>pull</i>
-1	-0.9	-0.73	-0.36	-0.3	0.27	0.36	0.55	0.82	0.91
Abstract									
<i>increase</i>	<i>succeed</i>	<i>obey</i>	<i>offend</i>	<i>respect</i>	<i>warn</i>	<i>argue</i>	<i>hope</i>	<i>rush</i>	<i>give</i>
-0.55	-0.36	-0.18	-0.1	-0.1	0.1	0.2	0.36	0.36	0.55

This procedure allows us to test whether participants' own intuitions about this semantic dimension of word meanings predict their propensity to experience the visual MQP as moving in one or the other direction. The mixed effects logistic regression model had the response (vertical or horizontal) as binary outcome, the directionality-ratings and the word type (concrete versus abstract) as fixed effects, and participant ID as random intercept.

$$\text{response} \sim \text{directionality rating} + \text{word type} + (1 \mid \text{participant ID})$$

$$\text{response} \sim \text{directionality rating} * \text{word type} + (1 \mid \text{participant ID})$$

Model comparison was used to test whether including an interaction term between the fixed effects yielded a better model fit.

2.5 Results

2.5.1 Staircasing session

In response to hypothesis 1, we found that step value significantly predicted participants experience of direction of motion in the motion quartet paradigm: linear component, $\beta = 17.15$ ($SE = 1.90$), $z = 9.01$, $p < 0.0001$, odds ratio > 10,000. This means that as the distance of the flickering dots becomes narrower on the horizontal plane, participants are more likely to report seeing horizontal motion and vice versa (see Figure 5(a)).

Figure 5: Participants' responses as a function of step value (a). As the aspect ratio of the MQP becomes more narrow, the probability of experiencing the visual illusion as a horizontal motion increase. To the right, variability of responses as a function of step value (b). As the step value of the MQP approach the center values (yielding symmetric aspect ratios), participants are more indecisive in their responses suggesting that they experience multistability of the percept.

In response to hypothesis 2, we found significant increase in response variability as the step values approach the center values, as indicated by the quadratic estimate of the model: $\beta = -0.22$ ($SE = 0.04$), $t = -5.04$, $p < 0.0001$. This suggests that as the MQP stimuli present more symmetric aspect ratios, participants are equally likely to experience a horizontal and a vertical illusion of motion supporting hypothesis 2 (see Figure 5b).

2.5.2 Experimental session

In response to hypothesis 3 and 4, we found that a model including the interaction term between directionality rating and word type explained significantly more variance than a simpler model without the interaction: $X^2(1,5) = 4.31$, $p < 0.05$. Therefore, we will concentrate on the interaction model.

We observe a significant main effect of word directionality ratings on response (i. e. the propensity to see the MQP as moving vertically or horizontally): $\beta = 0.74$ ($SE = 0.29$), $z = 2.56$, $p = 0.01$, *odds ratio* = 2.1. This indicates a general tendency that the directionality of word semantics primes the visual illusion with words denoting a vertical movement causing participants to experience the MQP as moving vertically while horizontally directed motion-words makes them perceive horizontal motion (notice, however, that it is recommended to be cautious with interpretations of main effects when there are significant interaction effects). We also observe a significant interaction effect: $\beta = -0.67$ ($SE = 0.32$), $z = -2.08$, $p = 0.037$, *odds ratio* = 0.51. This indicates, contrary to hypothesis 4, that the priming effect is stronger for abstract words than for concrete ones (see Figure 6 and Table 2).

Figure 6: The relation between ratings of directionality, response behavior and word type (abstract and concrete). Notice that abstract words seem to have a stronger priming effect on visual directionality responses than concrete words. The x-axis is scaled for normalization of individual uses of the rating scale. The value -1.0 corresponds to a 100% vertical rating, and 1.0 to a 100% horizontal rating (see also Table 1). The y-axis represents the probability of participants reporting horizontal motion in the MQP stimuli.

Table 2: Model estimates and stats.

	Estimate	SE	z-value	p-value	Odds ratio
(Intercept)	−0.65	0.29	−2.19	0.02*	0.52
Directionality rating	0.74	0.29	2.56	0.01*	2.10
Word type	−0.13	0.13	−0.99	0.32	0.87
Directionality rating * Word type	−0.67	0.32	−2.08	0.03*	0.51

2.6 Exploratory control analyses

Since the results indicate stronger directionality priming from abstract than concrete motion words, we ran a series of post hoc control analyses, exploring these effects. There might be distributional and semantic properties in the two verb-conditions that remain uncontrolled in the previous analyses but affect the results. Some suggestions will be elaborated below.

2.6.1 Word length

When examining the verbs in the two conditions of abstract and concrete word-categories, it appears that the two conditions contain words that vary slightly in length and number of syllables. This may be relevant considering that small differences in the duration of the auditory stimulus may have attracted attention in different ways (Pitt & Samuel 2006; Strauss & Magnuson 2008; Winsler et al. 2018). This had not been considered in the selection of the verbs. Indeed, the concrete words in this experiment turn out to be significantly shorter than the abstract words (although only marginally): $\beta = -1.1$ ($SE = 0.51$), $t = -2.14$, $p = 0.046$. Therefore, we tested the main model reported for hypothesis 3 and 4 including the fixed effect of word length measured in number of characters. Adding this variable to the model did not improve model fit: $X^2(1,6) = 2.75$, $p = 0.1$.

2.6.2 Word frequency

Another variable that was not systematically controlled in the main analysis is word-frequency. Word frequency has consistently been associated with the ‘accessibility’ of words, with more frequent words being easier and faster to recognize (Morrison and Ellis 1995). On the other hand, less frequent words might slow down processing and thus give rise to ‘deeper processing’ (Chwilla et al. 1995). In order to test potential effects of word frequency, word-frequency data was retrieved from the MRC Psycholinguistic Database (Coltheart 1981; Wilson 1988). Word frequency turns out not to differ significantly between the concrete and abstract words used in the experiment: $\beta = 3.22$ ($SE = 18.53$), $t = 0.17$, $p = 0.86$, and adding word frequency to the main model did not significantly improve the model fit: $X^2(1,6) = 1.57$, $p = 0.21$.

2.6.3 Word imaginability

Related to the point about levels of processing, the extent to which a word evokes rich and vivid representations could influence the potential for priming. The MRC Psycholinguistic Database also contain ‘imaginability ratings’ for a large number of words. Relying on this resource, we observe that the two words types differ significantly in their imaginability, with concrete words being more imaginable than abstract words: $\beta = 97.76$ ($SE = 27.55$), $t = 3.55$, $p < 0.01$. Adding imaginability to the main model also yields a better model fit: $X^2(1,8) = 6.53$, $p = 0.01$. Inspecting the estimates reveal that the original pattern of results still holds, with a significant main effect of directionality rating and interaction between directionality rating and word type, but in addition the variable of word imaginability also comes out significantly ($\beta = -0.003$ ($SE = 0.001$), $z = -2.55$, $p = 0.01$), suggesting that this variable explain some additional variance. Table 3 presents estimates for a model including all control variables.

Table 3: Model estimates and stats for control analyses.

	Estimate	SE	z-value	p-value	Odds ratio

(Intercept)	−0.13	0.84	−0.16	0.87	0.87
Directionality rating	1.38	0.61	2.27	0.023*	3.97
Word type	0.41	0.26	1.54	0.12	1.51
Word length	0.14	0.11	1.27	0.20	1.15
Frequency	0.001	0.002	0.69	0.49	1.00
Imaginability	−0.003	−0.001	−2.63	0.008*	0.99
Directionality rating * Word type	−1.35	0.61	−2.21	0.027*	0.26

3 Discussion

This study set out to investigate semantically activated cross-modal priming combining ideas from embodiment and metaphor theory with an approach to human cognition as a dynamical system. Using the motion quartet paradigm (Hock et al. 1993), we staircased participants to their individual multistable point of visual illusion, and then primed them with concrete and abstract words disguised as a Lexical Decision Task (Meyer and Schvaneveldt 1971). The aim was twofold: 1) to investigate whether participants' response behavior followed the principles predicted by dynamical systems theory and 2) to investigate whether the semantic processing of words affects participants' experience in a different modality, in this case vision, which could indicate that linguistic processing draws on and integrates with other cognitive systems.

Indeed, we found that participants, when presented with the MQP, experienced multistability and phase transitions between competing attracting states as a function of the control variable (distance between flickering points), replicating the results of the original study by Hock et al. (1993).

Second, we show that in contexts of multistability, the semantic directionality of motion words affects visual processing evoking the illusion of compatible directionality of motion in the visual modality. In other words, the auditory word stimuli seemed to enhance attractive states for motion-direction causing the semantically associated directionality to come into prominence. These observations indicate that the comprehension of words, a higher order cognitive process, can serve to structure and organize lower-level visual perception, at points where the visual perception is ambiguous, unstable, and disordered. This cross-modal priming effect suggests that the processing of otherwise different perceptual impressions (auditory lexical and graphic visual), is not unfolding in separate, compartmentalized modules as assumed in some models of human cognition (Chomsky 1986; Fodor 1983; Pinker 1994). Rather, our observations suggest interactivity between the higher-order and lower-level cognitive processes across modalities compatible with predictions coming from the theory of perceptual simulations (Barsalou 1999). Since semantic processing activates rich, multimodal representations, they can also interfere with these and thus affect our experiences in a different modality (see also Meteyard et al. 2007 for similar observations).

Interestingly, the effects observed in this study seem to be driven mainly by abstract words, while the concrete words yielded comparably weak effects. This goes against our hypotheses and predictions grounded in our theoretical starting point (Lakoff & Johnson 2008; Paivio 1990). Following embodiment theory, past experience of own concrete motion as well as the perception of other concrete motion events is considered the source domain structuring meaning in both concrete and abstract words (Lakoff 1987; Lakoff & Johnson 1999). However, in abstract concepts, this is thought to happen indirectly through metaphorical extension from the domain of concrete experience. Another suggestion, however, is that abstract concepts are also directly grounded in sensory-motor experiential content. Barsalou and Wiemer-Hastings (2005) thus argue that while the meaning of concrete concepts is simulated by reference to a more constrained type of referents, the semantics of abstract concepts are associated with introspective activation of more elaborated situations. That is, they still activate perceptual representations, but often of a relatively more varied character (Pecher et al. 2011). This might be one of the reasons why, in general, the abstract words used in this study score lower on imaginability: since concepts like *obey* and *respect* are not designating very particular referent scenes, but perhaps more intangible emotional aspects of a variety of different types of situations, they are slightly harder to 'imagine.' Yet, they might not be less experiential.

It is interesting to notice how participants' ratings of the verb-directions and the corresponding priming effects differ between concrete and abstract concepts. Considering the x-axis of Figure 6, we observe that the concrete verbs are associated with more clear-cut directions, reaching to each end of the rating scale indicating agreement in participants' assessment of motion-direction. In contrast, ratings of the abstract concepts cluster more around center values on the scale (−0.5 to 0.5), which could indicate that the direction associated with abstract verbs is more ambiguous, leading to more disagreement on the direction of abstract verbs. Interestingly, however, the ambiguously directed abstract verbs had a stronger effect on the response indicated by their distribution on the y-axis and the steeper slope of the regression model. That is, while concrete words are more

readily associated with explicit dimensions of directionality, the abstract concepts evoked stronger priming on the visual system. The cognitive mechanisms giving rise to this effect are not clear, but exploratory control analyses attest that the effect cannot be attributed to uncontrolled low-level variables such as word length or frequency. This motivates consideration of other semantic dimensions. In this regard, it is striking that the concrete concepts generally denote activities involving an individual agent preoccupied with physical motion as in examples *walk*, *lift*, *climb* and *pull*. In contrast, most of the abstract concepts denote inherently *social* situations, typically involving two agents in some relation: *obey*, *offend*, *argue*, and *warn*. Considering the strength of priming (corresponding to the distribution on the y-axis) of abstract words, it appears that concepts related to such socially interactive semantics seem to occupy the ends of the scale, thus driving the effect, while, for instance, the less social concept *hope* has almost no priming effect. We speculate that the semantic dimension of social interaction could be the latent factor driving the surprising results of our study. Revisiting the visual stimuli of the MQP we notice that the illusion could be perceived as a repeated iteration of motion going forth and back between two entities (the flickering dots). This might evoke a representation of interactive turn-taking between agents (e. g. as in an argument) rather than, say, unidirectional walking or lifting. Our social world is a very prominent factor in human consciousness and likely to be an important source domain for many aspects of human meaning making (Pascual 2006; Tylén et al. 2013). Whether the semantic dimension of social interaction indeed is the factor driving the results has to be reaffirmed in future studies more systematically manipulating this dimension.

It is important to consider factors that could potentially confound our results. In the choice of word stimuli, we adapted concrete and abstract words from Richardson et al. (2001). An advantage of using their word norms is that they also provide norms for directionality, which is crucial for our study. In their study, *bomb* is considered a concrete motion verb, while *give* is considered an abstract concept, and therefore they have been included as such in the present study. It could, however, be argued whether these norms hold, especially in the context of a different language. As there is, at present, no comprehensive concreteness norms available for Danish (and it is far beyond the scope of this study to provide such), the Richardson et al. (2001) norms were considered the best starting point. Furthermore, although all participants (except one) were native speakers of Danish, the experiment was carried out in English, which allowed us to adopt word lists and norms from Richardson et al. (2001). We assume generally high levels of English proficiency of our participants on the grounds that the university students included in the study were taking courses taught in English, and further, that most of the remaining participants were known to have good English skills. However, not all participants were known to the experimenter and their English proficiency was not controlled for. We cannot exclude the possibility that our results had been different if participants were tested in their native language. Likewise, it would have been advantageous to test all participants in the same environment.

Participants were tasked with judgements of directionality of individual verbs outside any discourse context. While this is a common procedure in psycholinguistics, it is not representative of most contexts of actual language use. Without proper contextualization it is difficult to predict exactly how a word is comprehended. Thus, individual variations in verb-comprehension might influence our results. Future studies could use sentences or narratives as the semantic prime to avoid such potentially confounding factors (e.g. Dils and Boroditsky 2010a, Dils and Boroditsky 2010b).

Another potential limitation regards participants' directionality ratings of the verbs. The participants received the questionnaire on email subsequent to the experiment, and thus we do not know when, where, and on what device they filled in the survey. Only twelve of the twenty-one participants answered the questionnaire which yields some uncertainty regarding the directionality scores used as a predictor for the response behavior of all participants.

The experiment was relatively complicated, as it required participants to hold an auditory word in memory, while being presented with the visual stimuli, and then to respond first to the visual stimuli, and then to the lexical decision task. Possibly, this could be a disadvantage of the experiment: if participants focused on holding the auditory word in memory to provide a correct answer in the lexical decision task, it could compromise their attention to the visual stimuli. However, the time span between the auditory presentation of the word and the lexical decision was kept rather short, and decisions were self-paced allowing participants to adjust to their preferred personal 'flow' of the experiment.

4 Conclusion

The aim of this experiment was to investigate the dynamic and multimodal nature of linguistic representations. More specifically, we tested whether auditory words can prime visual perception of apparent motion-direction which would suggest that verbal semantics rely on and thus can interfere with other modalities of

representations. This was examined by combining an auditory version of the Lexical Decision Task (Meyer and Schvaneveldt 1971) with the The Motion Quartet Paradigm (Hock et al. 1993). We found that words signifying horizontal and vertical motion primed the visual perception of compatible motion-direction in the motion quartet. This resonates with ideas from Embodiment theory that linguistic processing involves perceptual simulations (Barsalou 1999).

Interestingly, and contrary to our hypotheses, the priming effect was driven by abstract verbs, while concrete words had a comparably weaker effect. Controlling for word length, frequency and word imaginability did not change this pattern of results. We speculate that another semantic dimension, that is, the extent to which the words evoke association to social interaction might drive the results. While concrete words would mostly denote individual action, the abstract words would often refer to socially interactive situations involving two or more agents. The particular visual layout of the MQP might be more compatible with the general concept of repeated *exchange* between two agents than individual motion.

Further experimentation is needed to deepen the understanding of the mechanisms involved in lexical processing and multimodal representation. For example, it would be interesting to systematically manipulating the social nature of the concepts in order to further explore results from the present study.

A Appendix

Table 4: Table of test words and ratings. ‘V’ and ‘H’ stand for vertical and horizontal directions. ‘Ratings’ refers to participant-word-ratings of this study. ‘Norms’ refers to verb-directionality based on the norming-study of Richardson et al. (2001). Match and mismatch indicate whether there is direction-agreement between the ratings and the norms. As the words “climb” and “grow” were added later, there is no direction-estimation from the norming-study to these words. The reported experiment primarily used test-verbs selected from the list available in Richardson et al.’s (ibid.) study. However, two of the concrete and vertical words from the list were replaced because they appeared ambiguous in their directionality to the experimenter. Two other concrete and vertically directed words were added: “climb” and “grow” replaced “float” and “fly”.

Test-word Conditions	Words	Ratings	Norms	Match
concrete	Walk	0.727 (H)	H	Match
concrete	Point	0.364 (H)	H	Match
concrete	Push	0.545 (H)	H	Match
concrete	Pull	0.909 (H)	H	Match
concrete	Flee	0.818 (H)	H	Match
concrete	Lift	−1.000 (V)	V	Match
concrete	Climb	−0.900 (V)	?	Match
concrete	Sink	−0.364 (V)	V	Match
concrete	Grow	−0.727 (V)	?	Match
concrete	Bomb	−0.300 (V)	V	Match
abstract	Hope	0.363 (H)	V	Mismatch
abstract	Argue	0.200 (H)	H	Match
abstract	Rush	0.363 (H)	H	Match
abstract	Give	0.545 (H)	H	Match
abstract	Warn	0.091 (H)	H	Match
abstract	Succeed	−0.363 (V)	V	Match
abstract	Respect	−0.091 (V)	V	Match
abstract	Obey	−0.182 (V)	V	Match
abstract	Increase	−0.545 (V)	V	Match
abstract	Offend	−0.091 (V)	H	Mismatch
Filler-words				
concrete	Show	0.182 (H)	N	Mismatch
concrete	Hunt	0.636 (H)	N	Mismatch
concrete	Smash	−0.091 (V)	N	Mismatch
concrete	Impact	−0.182 (V)	N	Mismatch
concrete	Wash	0.000 (N)	N	Match
abstract	Rest	0.727 (H)	N	Mismatch
abstract	Tempt	0.091 (H)	N	Mismatch

abstract	Own	−0.182 (V)	N	Mismatch
abstract	Want	0.000 (N)	N	Match
abstract	Regret	0.000 (N)	N	Match

Notes

1 We had a limited time window for data collection and the sample size was thus determined by how many participants we could recruit in the designated timeframe.

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