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Inter-process relations in spatial language: Feedback and graded compatibility

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ABSTRACT

Mapping spatial expressions such as "behind the cup" to a spatial region requires two processes that have been largely explored independently: reference frame selection and spatial term assignment (Logan & Sadler, 1996). Reference frame selection carves a space into regions. Spatial term assignment evaluates these regions by determining the acceptability of the term for the given configuration. Here we present a systematic investigation of the relation and interplay of these two processes by asking whether (a) information from spatial term assignment feeds back to selection and (b) whether competition during selection is graded. In a series of simulation studies, we assess the performance of four computational models, each of which instantiates a unique combination of feedback (no feedback vs. feedback) and gradedness (all-or-none compatibility vs. graded compatibility). The results support two key observations about human spatial term use: First, reference frame selection and spatial term assignment proceed concurrently and in mutual interaction, with assignment information feeding back and influencing the selection process. Second, competition in reference frame selection is graded such that the strength of competition between different available reference frames increases continuously with decreasing similarity of the frames. As such, our work provides a new view on the components involved in spatial term use and their interplay, and suggests more broadly that the gradedness of competition may also be an important aspect of conflict and selection in other cognitive domains.

1. Introduction

People frequently communicate about their spatial surroundings to, for example, give directions, to warn of dangerous places, or to refer to a region of space that contains a desired object. Imagine, for example, that you are looking for the car keys and your significant other tells you "The car keys are near the plant". Such information is helpful because it reduces the space you need to search. As in this example, verbal communication of spatial relations and configurations often involves the use of spatial terms such as "above", "near", "in front of", etc., which indicate where to look for a certain object, called the *trajector* (e.g., the car keys), with respect to another object, called the *landmark* (e.g., the vase; Langacker, 1987).

Despite the seeming ease with which we employ spatial terms in our everyday lives, producing and comprehending spatial utterances such as "The car keys are near the plant" is a complex ability. In their influential computational analysis, Logan and Sadler (1996) identify four representations and four processes that are crucially involved in spatial term use. Much of the subsequent research on human spatial term use has focused rather independently on the nature of each of these representations and/or processes (e.g., Carlson & Logan, 2001; Coventry, Griffiths, & Hamilton, 2014; Miller, Carlson, & Hill, 2011; Struiksma, Noordzij, Neggers, Bosker, & Postma, 2011; but see Lipinski, Schneegans, Sandamirskaya, Spencer, & Schöner, 2012). However, a comprehensive understanding of human spatial term use also requires elucidating the interplay and interaction of the involved processes, including addressing such questions as *What information is exchanged between which processes? Which processes are dependent on which others? To what extent are processes executed in parallel or sequentially*?

In this paper, we present an in-depth analysis of the relation between two of the processes proposed by Logan and Sadler (1996): reference frame selection and spatial term assignment. Of main interest is whether spatial term assignment provides feedback to reference frame selection, and the degree to which such feedback is graded due to a dependence on the compatibility of the reference frames being considered for selection. We investigate the role of feedback and gradedness by comparing the performance of four computational models, each of which instantiates a unique configuration of feedback (no feedback

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vs. feedback) and gradedness (all-or-none compatibility vs. graded compatibility). The results of our model-based analyses (a) imply a new view on the components involved in human spatial term use and their interplay, (b) contribute to developing a comprehensive explicit computational account of human spatial term use, and (c) have implications for our view on conflict and selection in human cognition beyond the domain of spatial language.

We start with a brief review of key concepts and processes involved in the spatial language domain. Subsequently, we discuss possible relations among the processes of reference frame selection and spatial term assignment, and present four models that instantiate different possible relations. By means of a series of simulations, we assess the importance of assuming feedback and gradedness for accounting for pertinent empirical data. Finally, we discuss the theoretical implications that the simulation results have for our understanding of spatial term use as well as for human cognition more generally.

2. Components of spatial term use

We take as our starting point the computational theory of Logan and Sadler (1996) that has provided an influential and instrumental framework within which much of the subsequent spatial term literature has been interpreted. According to Logan and Sadler (1996), spatial term use can be assumed to involve two general procedures: selecting a reference frame and assigning a spatial term. These are accomplished with the following processes: spatial indexing, reference frame adjustment, spatial template alignment, and computing goodness of fit. Spatial indexing essentially establishes where “things” are in the spatial surrounding without identifying the nature of the indexed entities. Perceivable, distinguishable entities (e.g., landmark and trajector) are spatially indexed such that further processing can refer to them (Pylyshyn, 1989). Reference frame adjustment establishes a reference frame, which enables apprehending the spatial relation between landmark and trajector by setting up a correspondence between the physical world (spatial configuration of landmark and trajector) and its conceptualization (the perceived spatial relation between landmark and trajector). Spatially indexing and reference frame adjustment result in the selection from one or more available reference frames. Spatial template alignment brings a memory representation of a spatial term's regions of acceptability to bear on the considered spatial configuration such that the memory representation is aligned with the established reference frame. Computing goodness of fit draws on the aligned memory representation to determine how acceptable a given spatial term is for a given spatial configuration of landmark and trajector. These two processes give rise to the assignment of a spatial term.

In the work reported below, we focus on the relationship between reference frame selection and spatial term assignment, which have been both empirically and computationally investigated, though largely investigated independently, as summarized below.

2.1. Reference frame selection

The production and comprehension of spatial terms crucially requires and depends on dividing space into distinguishable regions. Without such division it would be impossible to selectively refer to specific parts of space using spatial terms. *Reference frames* are mechanisms for establishing the required division of space. As characterized by Logan and Sadler (1996), reference frames can be conceived as sets of coordinate axes with four parameters: origin (point in space on which the axes are centered), orientation (rotation of axes), direction (correspondence of axes' endpoints and spatial terms), and scale (the extent of the coordinate axes). The values of these parameters can be flexibly set based on context-dependent information. The process of reference frame selection is concerned with this setting of parameters.

Following a distinction introduced by Levinson (1996, 2003) that is prevalent in research on spatial term use (Ashley & Carlson, 2007; Bohnemeyer & O'Meara, 2012; Burigo & Sacchi, 2013; Carlson & van Deman, 2008; Carlson-Radvansky & Jiang, 1998; Danziger, 2010; Johannsen & de Ruiter, 2013; Li & Gleitman, 2002), we distinguish three main sources of information that can provide evidence for reference frame parameterization: *absolute*, *relative*, and *intrinsic*. The absolute source comprises evidence from environmental influences. For example, perceived gravity may provide evidence for the orientation and direction parameter of the reference frame such that the orientation of the vertical axis is aligned with gravity and “above” is defined as the direction opposite of gravity's pull. The relative source comprises evidence arising from the body of a person, who perceives the spatial configuration of landmark and trajector. This person will often be one of the participants of the conversation, but need not be. For example, the person's body orientation may provide evidence for the orientation and direction parameter of the reference frame such that the orientation of the vertical axis is aligned with the feet and head, with “above” defined as the direction toward the head. The intrinsic source comprises evidence arising from the properties of the landmark. For example, landmark orientation may provide evidence for the orientation and direction parameter of the reference frame such that the orientation of the vertical axis is aligned with the orientation of the top and bottom of the landmark and “above” defined as the direction toward the top.

Different sources of information may suggest different, conflicting parameterizations of the reference frame that may lead to different meanings for a given spatial term. For example, consider a situation as the one depicted in Fig. 1 and imagine that the standing person told the

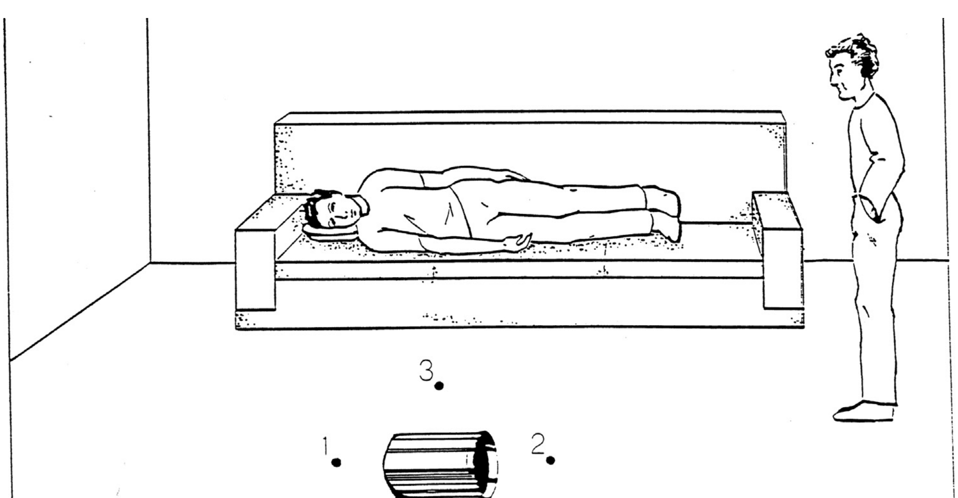

Fig. 1. Illustration of a situation that demonstrates the difference between absolute, relative and intrinsic reference frame: Given the utterance “The fly is above the trashcan” the figure shows three possible locations of the fly; one based on the absolute (1), one based on the relative (2), and one based on the intrinsic (3) reference frame. Reproduced from Fig. 1 of Carlson-Radvansky and Irwin (1993).