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Relating allocentric and egocentric survey-based representations to the self-reported use of a navigation strategy of egocentric spatial updating☆

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ABSTRACT

This study aimed to relate two different forms of survey-based representations encoded after real-world route learning to the differential use of allocentric and egocentric frames of reference, and a navigation strategy of egocentric spatial updating that focuses on the computations of self-to-object relations. Using sketchmaps and assessments of spatial and landmark knowledge, Study 1 implicated the existence of allocentric and egocentric survey-based representations that preserved survey knowledge of the environment based on the primary engagement of allocentric and egocentric frames of reference respectively. In Study 2, an egocentric spatial updating strategy scale was designed as part of a new self-report *Navigation Strategy Questionnaire (NSQ)*, and validated with regards to relevant behavioral measures of spatial and landmark knowledge. Notably, egocentric-survey map sketchers reported the highest scores on this new scale among three groups of map sketchers, supporting the proposal that they were highly involved in egocentric spatial processing during route learning.

1. Introduction

The classical model that describes the development of spatial knowledge is the sequential/stage model, *Landmark, Route, Survey (LRS)*, first proposed by Siegal and White (1975) and subsequently elaborated by Thorndyke and Goldin (1983). In this model, the representational knowledge of a new environment is proposed to progress sequentially from a foundational level of landmark knowledge to an intermediate level of route/procedural knowledge and finally to an advanced level of survey knowledge. *Landmark knowledge* is the first to develop during an initial period of familiarization; it includes mental images of discrete objects and scenes which are salient and recognizable in the environment. *Route/procedural knowledge* links together important, salient landmarks in a sequence and associates specific actions with them (e.g., "turn left in front of the library and walk straight past the benches"). It constitutes a type of non-spatial representation with three main aspects: i) the information of travel is accessed sequentially as an ordered list of different locations; ii) the number of alternative paths branching out from one path is small; and iii) a first-person perspective is adopted to decide on where to go from a given location (Siegal & White, 1975; see also; Werner, Krieg-Brückner, Mallot, Schweizer, & Freksa, 1997). With adequate familiarization or route exposure, representational knowledge acquired from traveling on different route segments gets integrated into *survey knowledge* (also termed as *configurational knowledge*) that pertains to a map-like network of objects/landmarks, termed as a *survey-based representation*. A survey-based representation is characterized by: i) spatial extent over a common coordinate or reference system; ii) abstract or symbolic mental representations of physical or geographical entities in the real world;

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and iii) metrically scaled information about distance and direction between environmental features (i.e., landmarks, routes, and districts) (Siegal & White, 1975; see also; Berendt, Barkowsky, Freksa, & Kelter, 1998). The survey-based representation, unlike route knowledge that is acquired though the sequential merging of segmented paths, is formed by the spatial integration of landmark configurations, and gives fast and route-independent retrieval of landmark locations (Thorndyke & Goldin, 1983; see also; Rothkegel, Wender, & Schumacher, 1998).

Despite being highly influential for decades, Siegal and White's (1975) LRS model has not received convincing empirical support. A number of studies had shown that the route knowledge acquired early on after direct exposure to a new environment did not always become survey knowledge despite repeated exposures (e.g., Chase, 1983; Gärling, Böök, Lindberg, & Nilsson, 1981; Ishikawa & Montello, 2006). For instance, Ishikawa and Montello (2006) showed that there were participants who consistently demonstrated poor estimations of directions and distances despite repeated route exposure, as well as others who demonstrated highly accurate performance on the same spatial measures from the very first session. In addition, another problem with the Siegal and White's (1975) LRS model is that it cannot account for an accumulating amount of evidence suggesting that the spatial memory of physical environments could be acquired and represented through two types of perspectives: the *first-person (field)* and *third-person (observer)* perspectives (see, e.g., Blajenkova, Motes, & Kozhevnikov, 2005; Hirtle & Hudson, 1991; Nigro & Neisser, 1983; Sutton, 2010; Taylor & Tversky, 1996; Werner et al., 1997). The first-person perspective is closely linked to one's visuo-perceptual experience (Herrmann, 1996) and assuming this perspective requires one to visualize or recall scenes from a body-centered field of view (Nigro & Neisser, 1983). In contrast, the third-person perspective is closely linked to a bird's eye or aerial view of a spatial layout (Cohen, 1989) and assuming this perspective requires one to imagine scenes from an external or disembodied vantage point (Nigro & Neisser, 1983).

In a previous study which implicated the involvement of these two perspectives in the formation of survey-based representations, Blajenkova et al. (2005) asked each of their participants to draw a sketchmap after traversing a route comprising of two levels in a previously unfamiliar building, and classified those sketchmaps into three categories: i) one-dimensional (1D) sketchmaps that showed landmarks connected in a sequential and non-spatial fashion; ii) two-dimensional (2D) sketchmaps that showed the route's spatial configuration on one plane which implicated the adoption of an aerial view; and iii) two-level three-dimensional (3D) sketchmaps that was exceptional for showing the spatial layout of each floor separately but in alignment along the vertical dimension. The finding of 3D sketchmaps was novel and interestingly suggested that their sketchers might have primarily engaged the first-person perspective while generating survey-based representations. Overall, these results showed that individual differences in the formation of environmental representations exist and highlighted that certain individuals could acquire survey-based representations after just one exposure to a novel environment. In view of this research, the traditional stage-like procedure of route learning—characterized by first attending to landmark and route information, followed by abstract mapping of inter-relationships between landmarks or places (Thorndyke & Goldin, 1983; Thorndyke & Hayes-Roth, 1982)—should then not be considered as the only way that could lead to the formation of survey-based representations.

1.1. Spatial navigation through egocentric spatial updating

Over the past three decades, numerous studies have offered strong evidence for the existence of a special mode of navigation called *spatial updating* (e.g., Farrell & Thomson, 1998; Klatzky, Lippa, Loomis, & Golledge, 2003; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Klatzky et al., 1990; Loomis, Klatzky, Philbeck, & Golledge, 1998; Loomis, Lippa, Klatzky, & Golledge, 2002; Loomis et al., 1993; Wang & Brockmole, 2003; Wang & Spelke, 2000; Wang et al., 2006). Importantly, several researchers have proposed that spatial updating can exist through two formats or reference systems in which egocentric (self-to-object) and allocentric (object-to-object) spatial relations are processed respectively (see, e.g., Burgess, 2006; Hodgson & Waller, 2006; Mou, McNamara, Valiquette, & Rump, 2004; Rump & McNamara, 2013; Sholl, 2001; Wang et al., 2006). For the purpose of this current research, this paper focuses on the greater relevance of egocentric spatial updating for navigation as it has been suggested to be more involved in forming an online representation of the location of surrounding landmarks as one moves (see, e.g., Rieser, 1999; Wang & Brockmole, 2003) and that the egocentric experience that is inherent in its use has been proposed to contribute to the selection and encoding of reference directions in long-term spatial memory (see McNamara, Rump, & Werner, 2003; Rump & McNamara, 2013). Hence, in this paper, spatial updating is defined in egocentric terms as a dynamic process whereby a navigator continuously computes and updates transient self-to-object relations towards surrounding objects/landmarks or locations while traversing a path (see Amorim, Glasauer, Corpinot, & Berthoz, 1997; Loomis et al., 1998; Philbeck, Klatzky, Behrmann, Loomis, & Goodridge, 2001). During egocentric spatial updating, a navigator relies on internal (idiothetic) signals (i.e., proprioception and vestibular feedback) and external (allothetic) signals (i.e., acoustic and optic flow) to continuously compute estimates of self-position and orientation within external space (Loomis, Klatzky, Golledge, & Philbeck, 1999). In its basic form, egocentric spatial updating is known as *path integration* (also called *dead reckoning*, Loomis et al., 1999). It has been found to be practiced by animals like gerbils (Mittelstaedt & Mittelstaedt, 1980), desert ants (Müller & Wehner, 1988; Wehner & Wehner, 1986), and golden hamsters (Etienne, 1980; Etienne, Maurer, Saucy, & Teroni, 1986), and is normally characterized by a navigator's continuous updating of the location of a starting point relative to his/her current position and orientation during locomotion (Loomis et al., 1999; see also; Wiener, Berthoz, & Wolbers, 2011). In terms of similarity, both path integration and egocentric spatial updating rely largely on an egocentric frame of frame (akin to the first-person perspective) (Klatzky, 1998) or an egocentric representation system (Mou et al., 2004)—also known as a body-centered spatial framework (Bryant, Tversky, & Franklin, 1992; Franklin & Tversky, 1990; Tversky, Morrison, Franklin, & Bryant, 1999)— to compute and represent the location and orientation of surrounding objects with respect to the navigator's body. Principally, it is this dependence on the egocentric (body-centered) representation system or framework that distinguishes egocentric spatial updating from the higher level of route-based learning that is characterized by survey knowledge acquisition through survey-based (metric) navigation (see Trullier, Wiener, Berthoz, & Meyer, 1997).

In contrast to egocentric spatial updating, survey-based navigation centrally relies on an allocentric reference frame (akin to the third-person perspective) (Klatzky, 1998) or an environmental representation system (Mou et al., 2004; see also; Sholl, 2008) to visualize the coordinates of objects, landmarks and places and their interrelationships. This allocentric or environmental reference system has been widely implicated to be recruited in the storage of offline or long term/comprehensive spatial memories of configurations of objects or landmarks (see, e.g., Shelton & McNamara, 2001; McNamara et al., 2003; Mou et al., 2004; Mou & McNamara, 2002; Mou, Liu, & McNamara, 2009; Mou, Zhao, & McNamara, 2007). Based on spatial knowledge assessment of the relative locations of objects, spatial memories of object arrays have been suggested to be organized allocentrically according to the intrinsic reference axes of