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When Going the Right Way is Hard to do:
Distinct Phases of Action Compatibility in Spatial Knowledge Development

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Abstract

The present study explores spatial knowledge development using online response measures available in mouse tracking. Online measures can reveal cognitive processing masked in post-processing measures. In the study, participants verified spatial descriptions by moving the mouse to a YES or NO button. Mouse tracking software (Freeman & Ambady, 2010) recorded mouse trajectories. Results demonstrated action-compatibility effects (ACE), differing as a function of spatial knowledge development. For well-developed spatial knowledge, the ACE reflected the physical spatial relationship (e.g. response button on right, but building to the left). In terms of temporal dynamics, this effect occurred later in the response. For less-developed knowledge, the spatial term drove the ACE (e.g., response button on right, but description used term *left*). In this case, the ACE was immediate and continuous. As would be consistent with learning, ACEs were observed more probably with proximal than distant locations. From these results, we infer that perceptuo-motor associations build with time and experience and can play an integral role in retrieval from well-developed spatial representations.

Keywords: Spatial knowledge development, Embodiment, Action-compatibility effect, Perceptuo-motor integration, Online Measure

When Going the Right Way is Hard to do:

Distinct Phases of Action Compatibility in Spatial Knowledge Development

1. Introduction

Recall your first few months in college. Early on you learned the locations of your dormitory and the dining hall. With time you became familiar with frequently visited buildings (the gym, the library, and your friends' dorms) and your mental representation added more locations and connections between locations (Siegel & White, 1975). Learning the campus was grounded in your actions and perceptions; you made associations between the places you visited and the things you did and saw. How might these perceptions and actions shape spatial knowledge development? The extant literature on spatial knowledge development cannot answer this question, because it has largely measured spatial knowledge off-line rather than thinking about how space might entail situated simulation (Shelton & McNamara, 2004), or a mental re-experiencing of perceptual and motoric memories. To address this knowledge gap, we assessed whether online measures could reveal evidence of these simulations, and how the nature of these simulations may change as spatial knowledge develops.

1.1 Perceptuo-motor association in spatial representation

Single-cell recordings in animals suggest that spatial memory may incorporate perceptual and motoric traces of environmental experiences. Head-direction cells, observed in several mouse brain areas, fire when the animal's head faces a particular direction within a learned environment, regardless of the animal's body position (Taube, Muller, & Ranck, 1990). Associations between head-direction and landmarks build up during exploration and then guide navigation when re-entering the environment, even in the absence of visual landmark

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4 information (Taube, 2007; Zhang, 1996). When landmarks remain absent, head-direction cells
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6 build new associations, but also return quickly to original responses if a learned landmark
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8 reappears. The human equivalent of head-direction cell responses, which are in relation to
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10 vestibular and proprioceptive information, could be neural contributors to simulated spatial
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12 orientation (Jacobs, Kahana, Ekstrom, Mollison, & Fried, 2010).
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16 Whereas studies have examined how navigators actively use perceptual and motoric
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18 information when learning environments (e.g., Brunyé & Taylor, 2008a; Wang & Spelke, 2002;
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20 Mou, McNamara, Valiquette, & Rump, 2004), few have explored how long-term spatial
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22 memories might incorporate perceptuo-motor information and how such information may guide
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24 spatial knowledge retrieval. In one study, Zetzsche, Wolter, Galbrath and Schill (2009) had
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26 participants explore virtual environments that either complied with or violated Euclidean
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28 geometry (e.g., angles in a triangle summed to greater than 180°). Violations of Euclidean
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30 geometry should impede development of an abstracted, survey representation. Participants then
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32 had to find the shortest route from a new starting point in a test environment that also either
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34 complied with or violated Euclidean geometry. Results demonstrated that participants could
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36 successfully travel the shortest route without noticing Euclidean geometry violations. This
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38 suggests that navigation, instead of being based on abstracted, image-like representations, is
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40 primarily guided by representations that integrate sensorimotor information consistent with
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42 learning. In a study from our laboratory, Brunyé, Mahoney, and Taylor (2010) demonstrated that
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44 people use perceptuo-motor cues (footstep sounds) to shape spatial memories; when studying
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46 described routes, participants read faster and assumed they had walked farther when listening to
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48 fast relative to slow footstep sounds.
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4 How might use of perceptuo-motor associations in memory change as spatial
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6 representations develop? Studies on spatial knowledge development to date cannot address this
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8 question as they have taken different approaches using different methodologies (Brunyé &
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10 Taylor, 2008b; Brunyé, Rapp, & Taylor, 2008; Evans, Marrero, & Butler, 1981; Foo, Duchon,
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12 Warren, & Tarr, 2005; Foo, Warren, Duchon & Tarr, 2007; Hermer & Spelke, 1994, 1996;
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14 Montello, 1998; Pazzaglia & Taylor, 2007; Shelton & McNamara, 2004; Siegel & White, 1975;
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16 Taylor, Naylor & Chechile, 1999; Thorndyke & Hayes-Roth, 1982; Yeap & Jefferies, 2000;
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18 Zetsche et al., 2009). Perhaps because the approaches differed, debates remain about how
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20 spatial knowledge progresses with time and experience (Evans et al, 1981; Hermer & Spelke,
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22 1994, 1996; Montello, 1998; Siegel & White, 1975). One debated point revolves around the type
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24 of spatial information encoded as representations develop (e.g., Montello, 1998; Foo et al., 2005,
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26 2007; Siegel & White, 1975). Does the represented information progress systematically from
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28 landmarks to routes to configurations (Siegel & White, 1975) or do these information types build
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30 into representations in parallel (Evans et al, 1981; Hermer & Spelke, 1994, 1996; Montello, 1998;
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32 Yeap & Jefferies, 2000)? Still another view suggests that spatial memories may not be simply
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34 isomorphic map-like mental structures, but rather preserve perceptuo-motor information about
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36 environmental experiences (Regier & Carlson, 2001; Taylor & Brunyé, in press; Tversky, 2005;
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38 Tversky & Hard, 2009). This latter notion contrasts with earlier theories positing that vast
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40 amodal connectionist networks code for spatial knowledge (Kuipers, 1978; McNamara, 1991;
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42 Stevens & Coupe, 1978).

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48 If spatial representations incorporate perceptuo-motor associations, then the extent to which
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50 they do so should vary as a function of certain environment features. One of these features would
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52 be proximity between locations. People more likely interact perceptually and motorically with
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4 spatially proximal buildings than with distant ones. They see the relative location of two
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6 buildings with a slight turn of their head. People associate locations relative to coordinate axes of
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8 their body (Franklin & Tversky, 1990; Longo & Lourenco, 2007; Parsons, 1994; Tversky, 2005;
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10 Witt, Proffitt, & Epstein, 2004). For example, they process spatial relations in front of their body
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12 faster than those in back (Franklin & Tversky, 1990). For locations in close proximity, one can
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14 make these perceptuo-motor associations. Spatial language studies also suggest that during
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16 comprehension people integrate information about object proximity and object function (Carlson
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18 & Kenny, 2006; Logan & Sadler, 1996; Regier & Carlson, 2001). Actions related to specific
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20 objects appear to be represented and proximity between objects then facilitates responses to
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22 spatial utterances. In contrast, when landmarks are distant, people cannot make such associations
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24 and instead may draw on a more abstracted representation (Foo et al., 2005, 2007; Siegel &
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26 White, 1975). Travelers moving through an unfamiliar environment may orient on a distant
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28 landmark or use cardinal directions to guide navigation. Route planning studies also suggest that
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30 wayfinders rely on visual details to guide navigation within a proximal area, but on a coarse
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32 image-like representation for planning routes to distant spaces (Hölscher, Tenbrink, & Wiener,
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34 2011; Wiener & Mallot, 2003). As distant landmarks are not readily associated to body motions,
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36 perceptuo-motor associations between distant locations may either not develop or may not have
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38 the same strength as those between proximal landmarks.
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48 *1.2 Online measures of embodied spatial cognition*

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50 Online measures of cognitive processing may provide insights into spatial knowledge
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52 development. Offline measures, such as map drawing, pointing, or spatial statement verification,
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54 reflect the end product of how people use their spatial representation. As such, they may reflect
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56 numerous cognitive operations, some strategic. In contrast, because online measures are closer in
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4 time to the cognitive process, they are less likely to reflect strategic processing. Online measures
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6 more likely reflect first-pass, immediate task analysis (e.g., Marslen-Wilson & Tyler, 1976).
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8 Comparisons of online and offline measures suggest that they tap different aspects of cognitive
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10 processing (e.g., Kempler, Almor, Tyler, Andersen, & MacDonald, 1998). To our knowledge,
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12 the present study is the first to use an online measure, mouse tracking, to explore spatial
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14 representations and their development. The program *Mouse Tracker* (Freeman & Ambady, 2010)
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16 records real time x -, y - coordinates of the computer mouse at an approximately 60-75 Hz
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18 sampling rate. Mouse trajectory data with this spatial and temporal fidelity should be sufficiently
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20 rich to discover perceptuo-motor traces involved in spatial memory retrieval.
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26 Using mouse tracking to assess spatial representations draws on work taking an embodied
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28 approach (e.g., Glenberg & Kaschak, 2002; for reviews, see Barsalou, 2008; Fischer & Zwaan,
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30 2008). Theories of embodied cognition suggest that knowledge representation captures the
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32 perceptions and actions associated with learning (e.g., Barsalou, 2008; Barsalou, Simmons,
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34 Barbey, & Wilson, 2003; Casteel, 2011; Fischer & Zwaan, 2008; Hommel, Müsseler,
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36 Aschersleben, & Prinz, 2001). Spatial knowledge can involve both perceptual (e.g., spatial
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38 position) and motor (e.g., orientating) information associated with learning. For example, when
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40 recalling the relative spatial relationship between locations, navigators might simulate orienting
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42 to one location and visualizing the other, similar to what they experienced when learning the
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44 environment. That is, when thinking about one location with respect to another, situated
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46 simulation would activate similar sensorimotor neural representations to those active when the
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48 environment was learned (Shelton & McNamara, 2004).
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54 55 *1.3 Action compatibility paradigm* 56 57 58 59 60 61

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4 Action compatibility paradigms may provide behavioral evidence of any tacit reactivation
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6 of perceptual and motor experiences during spatial memory retrieval. This reactivation has been
7
8 referred to as *motor resonance*. Such paradigms have shown perceptuo-motor processing in
9
10 language comprehension. For instance, in Zwaan and Taylor's (2006) study, participants made
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12 sensibility judgments to sentences such as "Mark turned left at the intersection" more quickly
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14 when turning the response knob leftward compared to rightward. Such studies suggest that
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16 reading action words leads to mental simulation and motor resonance. If the motor resonance is
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18 compatible with concurrent motor processes, an "action-compatibility effect" (ACE) occurs
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20 (Glenberg & Kaschak, 2002), i.e. concurrent motor processes sharing directionality with the
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22 simulation can be facilitated and those incompatible with it can be impeded (Knoblich & Flach,
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24 2001; Repp & Knoblich, 2004).
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31 Studies on gestures in spatial cognition suggest a strong relation between spatial
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33 representations and hand movements (Alibali, 2005; Emmorey, Tversky & Taylor, 2000;
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35 Hostetter & Alibali, 2008). Using spatial knowledge, particularly giving directions, frequently
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37 involves hand movements. Although anecdotal, simply try describing a spatial layout while
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39 sitting on your hands. Many people in this situation have difficulty and some invoke head
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41 movements to compensate. In a more empirical approach, Emmorey et al (2000) analyzed
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43 spontaneous gestures of individuals asked to describe a map they had just studied. Although this
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45 study's goal was to compare route versus survey description gestures, the important point for the
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47 current work is that all participants gestured. While the mapping between hand movements and
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49 spatial representations of buildings might not be as direct as with other actions and responses
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51 (e.g., giving or grasping objects), spontaneous gesture use with spatial descriptions, even to an
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4 imaginary conversational partner, strongly suggests a connection between hand movements and
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6 spatial representations.
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9 Other research further strengthens this point. Other spatial description studies propose
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11 that gestures reflect spatial mental representations rather than the semantics of the spatial
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13 description (Goldin-Meadow & Beilock, 2010; Hostetter & Alibali, 2008; McNeil, 1992). When
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15 gestures are impeded, spatial descriptions become slower and less fluent. Further, people used
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17 different gestures when required to describe spatial information with different perspectives or
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19 diverse goals (Emmorey et al, 2000). Spatial problem solving, even without the goal to
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21 communicate to others, also elicits gestures (Kessell & Tversky, 2005).
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25 Hints from the gesture literature suggest the connection between spatial knowledge
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27 retrieval and hand movements. As such, tracking mouse movements when verifying spatial
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29 relations might reflect how spatial knowledge integrates motor associations. Specifically, mouse
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31 tracking can be used to examine action compatibility, taking advantage of the fact that motor
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33 movements can reflect the qualitative nature of mental representations (Barsalou, 1999; Beilock
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35 & Holt, 2007; Fischer & Zwaan, 2008; Goldin-Meadow & Beilock, 2010; Glenberg, 1997). If
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37 spatial memory retrieval involves the reactivation of perceptuo-motor memory traces, then
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39 measuring mouse trajectories during spatial memory retrieval may show evidence of action
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41 compatibility. Further, mouse tracking can reveal the magnitude and time course of any
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43 compatibility effects (Freeman & Ambady, 2010; Richardson, Dale, & Spivey, 2007; Spivey,
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45 Richardson, & Dale, 2009).
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53 One important issue should be noted. When presenting spatial information, situated
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55 simulations might not have a single basis. If motor resonance is activated by representations of
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57 spatial locations, the ACE would occur when the concurrent motion direction is congruent with
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4 the physical spatial relation. If the task is to verify a spatial relation, however, to-be-related
5 information needs to be conveyed so it can be verified. Processing even a simple directional term
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7 can activate the motor system (Müsseler & Hommel, 1997; Hommel & Müsseler, 2006). Thus,
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9 when verifying a spatial description, motor resonance might also be activated by the semantic
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11 terms used. In this case, the ACE would occur when the direction of concurrent motion is
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13 congruent with the directional term. Thus, evidence of an ACE might have either a spatial and/or
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15 a semantic basis. Because adults would have extensive experience processing spatial terms, but
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17 spatial representations of an environment would necessarily develop over time, the basis of an
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19 ACE may change as a spatial representation develops (Tomasino, Guatto, Rumiati, & Fabbro, in
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21 press). The present study considers this possibility. Distinct bases for ACEs can only be
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23 disentangled with incorrect, but not correct, spatial descriptions. If a spatial description matches
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25 the actual spatial relations, any motor resonance activated by retrieving spatial knowledge would
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27 be consistent with both the spatial relation and the directional term. Thus, the ACE observed
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29 with confirming spatial descriptions may reflect spatial and/or semantic processing. For an
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31 incorrect spatial description, the actual spatial relation would be different from the directional
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33 term, allowing for a separation between spatial and semantic basis for ACEs.
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43 The present study used mouse tracking to explore two fundamental questions related to
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45 spatial representations and their development. These questions include: 1) do spatial
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47 representations show evidence of reactivation of perceptuo-motor memory traces developed
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49 during learning; 2) if so, does the nature of the perceptuo-motor trace change as the
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51 representation develops, i.e. with more time and experience. To examine motor resonance
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53 consistent with learning, participants verified relative spatial locations, both proximal and distant
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55 from one another, described through language. As detailed above, proximal locations should
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4 have more perceptual and motor associations. The study design also allows for the fact that
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6 spatial terms should elicit perceptual and motor associations (Glenberg & Kaschak, 2002) and
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8 that these can be disentangled from perceptual and motor associations elicited by spatial
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10 knowledge. To examine spatial representations at different development stages, we recruited
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12 undergraduates with varied campus experience, using experience level as a proxy for earlier and
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14 later stages of spatial knowledge development.
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18 19 **2. Method**

20 21 *2.1 Participants*

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23 Forty-nine Tufts undergraduates (23 male, 26 female) participated individually for
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25 monetary compensation. Participants included 22 first-years, 5 sophomores, 13 juniors and 9
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27 seniors.
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30 31 *2.2 Stimuli and Design*

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33 The stimuli consisted of names and pictures of fifty Tufts University buildings familiar to
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35 undergraduates. Building pictures, used to confirm front door locations, depicted the front-door
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37 side of the building, but avoided showing information about adjacent locations. Test trials used
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39 building names. On a given trial, participants saw two building names and a spatial term relating
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41 them (e.g., Dowling Hall, Eaton Hall, left).
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46 The experiment used a 2 (*Familiarity*: low, high) \times 2 (*Congruency*: congruent,
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48 incongruent) \times 2 (*Proximity*: proximal, distant) \times 2 (*Description Correctness*: correct, incorrect)
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50 mixed-factor design. Description correctness, proximity, and congruency served as within-
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52 participant variables and familiarity served as a between-participant variable. *Familiarity* was
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54 operationalized by how long participants had been at Tufts. First-year and sophomore students
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56 comprised the low-familiarity group (27 participants); juniors and seniors made up the high-
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4 familiarity group (22 participants). *Congruency*, used to examine ACE, reflected the relation
5 between the direction the mouse would be moved for an accurate response and the direction
6 defined either by the spatial relationship between locations or the directional term. Response
7 movement is *spatially congruent* if it is in the same direction as that defined by the spatial
8 relationship between buildings. *Semantic congruency* compares mouse movement direction to
9 the direction named by the spatial term (e.g. *left*). These different congruency definitions were
10 separable for incorrect descriptions. For example, if the spatial description “Psychology building,
11 Post office, right” is incorrect, the actual spatial relation between the buildings is to the left. A
12 spatially-based ACE may attract mouse movement toward the left, the direction defining the
13 spatial relationship. In contrast, a semantic-based ACE would attract mouse movement toward
14 the right, in the direction the term describes. As fillers we included trials unrelated to leftward or
15 rightward movement (“front” and “back”), but did not include these in any analyses. *Proximity*
16 defined the physical proximity between buildings. Proximal trials described buildings physically
17 adjacent to each other. Distant trials described buildings distant from and not within visible range
18 of each other. *Description Correctness* reflected the described spatial relationship accuracy and
19 was responded by either “Yes” (correct) or “No” (incorrect). Note that an incorrect description
20 always described the spatial relationship as being opposite from the actual relationship, rather
21 than in an orthogonal direction.

2.3 Procedure

22 Before beginning the formal experiment, participants viewed a list of Tufts buildings and
23 verbally confirmed each building’s front door location. If they did not remember, the
24 experimenter showed them the building picture depicting the front door. After confirming the
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4 front door for each building, participants began the spatial relationship trials, presented using
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6 Mousetracker 2.12 (<http://mousetracker.jbfreeman.net/>).
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9 For each spatial relationship trial, a start button appeared, centered at the bottom of the 19-
10 inch monitor. Participants clicked the start button and the reference building name appeared,
11 centered on the screen for 1000ms, followed below it by the target building name, for another
12 1000 ms, and finally below the target name a directional term (“left”, “right”, “forward” or
13 “back”). Participants were to imagine facing the front door of the reference building and judge
14 whether the directional term correctly described the relative location of the target building (e.g.,
15 Facing *Dowling Hall*, *Eaton Hall* is to your *Left*). 500ms after the directional term appeared, the
16 “YES” /“NO” response buttons appeared in the upper left and right corners and the mouse
17 became active and visible. The building names, directional term, and response buttons remained
18 visible until the participant responded. If participants responded accurately, the next trial started.
19 For inaccurate responses, the program displayed an “X” for 1000ms. When participants took
20 longer than 5 seconds to respond, “time out” appeared. After each trial, the screen was blank for
21 500ms before the next trial.
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41 Participants completed 6 practice trials to familiarize themselves with the procedure. The
42 experiment involved 100 trials, presented in random order, that included 10 trials each in the 8
43 conditions defined by the three within-participants variables (congruency, proximity and
44 description correctness) plus 20 front/back filler trials. Half of participants had the “Yes” button
45 at the upper right corner and the “No” button at the upper left corner, and half had the reverse
46 placement. Both male and female participants completed the same procedure to examine gender
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58 *2.4 Dependent Variables and Coding*

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4 Dependent variables included accuracy, response time (RT), and mouse trajectory data, all
5 recorded by MouseTracker. Accuracy measured whether participants answered correctly. RT
6 measured the time (msec) between participants clicking the start button and clicking the response
7 button. We analyzed only RTs of accurate responses. MouseTracker records the mouse's raw
8 position data (x-y coordinates) over time, allowing us to calculate three trajectory-related
9 variables--*initial time*, *area under the curve (AUC)*, and *proportional Euclidean proximity (PEP)*.
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11 *Initial time* measured the time between when the mouse became active and the moment the
12 participant first moved the mouse, potentially indicating participant confidence in their judgment.
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14 AUC is the area between the actual and an idealized trajectory, a straight line between the start
15 and endpoint. Thus, positive AUC, with the mouse trajectory above the idealized trajectory,
16 indicates mouse movement attracted toward the opposite response and negative AUC, with the
17 mouse trajectory under the idealized one, indicates mouse movement attracted by the expected
18 response. AUC directly demonstrates the extent to which mouse trajectories are attracted by the
19 opposite response. PEP also measures the extent to which the mouse moved closer to the
20 opposite response and is calculated as $(1 - \text{distance} / \text{max}(\text{distance}))$. "Distance" in the equation
21 represents the Euclidean proximity between the mouse position at each time-step and the
22 incorrect response button. More importantly, PEP allows an examination of the mouse
23 movement's temporal dynamics. To do so, we rescaled individual trial trajectories into a
24 standard coordinate space and normalized them into 101 time-steps, using linear interpolation.
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26 We then combined the time-steps into five time bins (time-steps: 1-20, 21-40, 41-60, 61-80, 81-
27 101) and averaged PEP for each time bin. Plots of trajectory data show the 101 time-steps. For
28 ease in interpreting the graphs, the x-coordinates ranged from -1 to 1 and the y-coordinate ranged
29 from 0 to 1.5 (with x- and y-axes intersecting at "-1, 0").
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3. Results

We eliminated six low-familiarity and two high-familiarity participants for low accuracy (less than .60). Preliminary analysis showed no effect of response button position or gender, so analyses collapsed across these variables. We analyzed correct and incorrect descriptions separately due to their interactions with the spatial and semantic definitions of congruency. Analyses of accurate responses, for both correct and incorrect descriptions, consisted of 2 (Familiarity: low, high) \times 2 (Congruency: congruent, incongruent) \times 2 (Proximity: proximal, distant) mixed model ANOVAs on accuracy, RT, initial times, and AUC data. The PEP analyses also included Time bin with 5 levels. Except for accuracy, only accurate responses were submitted into analyses. The mouse trajectory results, because they are central to the current study's goals, were primarily analyzed and discussed. We only report significant effects here.

3.1 Correct descriptions

Mouse Trajectory Results

Mouse trajectory analyses showed an effect of congruency in AUC [$F(1, 39) = 52.440, p < .001, MSE = .194$]. For correct descriptions, *congruency* reflects both spatially-based and semantically-based definitions. Consistent with the ACE, mouse movements were closer to the opposite response during incongruent [$M = .961, SD = .697$] than during congruent trials [$M = .463, SD = .488$] (see Fig.1). In other words, when having to move the mouse in a direction opposite from the actual relative direction between landmarks or the direction described by spatial terms, mouse movement gravitated toward the spatially and semantically congruent response and away from the accurate response.

Examining the time-course of this response, the PEP data revealed an interaction between congruency and time bin [$F(4, 156) = 5.148, p = .001, MSE = .003$]. Fig.2 illustrates the degree

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4 to which the mouse traveled closer to the incorrect response over time. During incongruent trials,
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6 mouse trajectories showed more attraction to the opposite response, especially in the middle of
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8 the response (bin 3), compared to movement during congruent trials [$F(1, 39) = 26.55, p < .001$].
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11 *Accuracy and RT*

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14 For accuracy, responses to correct descriptions showed a marginal effect of proximity [F
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16 (1, 39) = 3.176, $p = .083$, MSE = .016]. Participants responded more accurately to proximal [M
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18 = .806, SD = .146] than to distant [M = .770, SD = .147] landmarks. Additionally, high-
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20 familiarity participants [M = .828, SD = .137] responded more accurately than low-familiarity
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22 ones [M = .750, SD = .148, $F(1, 39) = 8.423, p = .006$, MSE = .029]. These main effects were
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24 qualified by an interaction between familiarity and proximity [$F(1, 39) = 4.130, p = .049$, MSE
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26 = .016]. Low-familiarity participants responded more accurately to proximal locations than
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28 distant ones [$d = M_{\text{proximal}} - M_{\text{distant}} = .076, F(1, 39) = 7.46, p = .009$]; high-familiarity
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30 participants showed no proximity effect [$d = M_{\text{proximal}} - M_{\text{distant}} = -.005, F(1, 39) = .03, p = .862$]
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32 (see Table 1 for means).
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38 The accuracy results also showed an interesting, albeit marginal, three-way interaction
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40 between familiarity, proximity and congruency [$F(1, 39) = 3.478, p = .07$, MSE = .014] (see
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42 Table 1 for means). As shown in Fig.3, low-familiarity participants showed a marginal
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44 interaction between proximity and congruency [$F(1, 39) = 2.84, p = .100$, MSE = .04] such that
45
46 the compatibility between the concurrent motion direction and spatial representation and/or
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48 directional term somewhat facilitated judgments of proximal locations [$d = M_{\text{incongruent -}}$
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50 $M_{\text{congruent}} = -.072, F(1, 39) = 3.33, p = .067$], but not distant locations [$d = M_{\text{incongruent -}}$
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52 $M_{\text{congruent}} = .014, F(1, 39) = .25, p = .621$]. No such interaction was evident with high-familiarity
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57 participants [$F(1, 39) = .92, p = .343$, MSE = .01].
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4 The RT analysis also showed an effect of proximity [$F(1, 39) = 8.756, p = .005, \text{MSE} =$
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6 87452.455]. Consistent with the accuracy results, participants responded faster to proximal [$M =$
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8 1379.639, $SD = 494.554$] than to distant landmarks [$M = 1876.188, SD = .609.183$].
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10 11 3.2 Incorrect descriptions

12 13 *Mouse Trajectory Results*

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15 Analysis of initial time showed an interaction between familiarity and spatial congruency
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17 [$F(1, 39) = 7.258, p = .010, \text{MSE} = 32236.602$]. As Fig.4 illustrates, low-familiarity participants
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19 took longer to start moving the mouse on semantically incongruent trials [$d = M_{\text{incongruent}} -$
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21 $M_{\text{congruent}} = 80.731, F(1, 39) = 4.25, p = .046$] while high-familiarity participants took longer to
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23 start moving on spatially incongruent trials, although the difference was marginal [$d = M_{\text{incongruent}}$
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25 $- M_{\text{congruent}} = 70.401, F(1, 39) = 3.07, p = .087$] (see Table 2 for means). Keep in mind that for
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27 incorrect descriptions a spatially congruent trial is a semantically incongruent trial.
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33 The AUC results also showed an important three-way interaction between familiarity,
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35 proximity and spatial congruency [$F(1, 39) = 10.305, p = .003, \text{MSE} = .345$] (see Table 2 for
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37 means). For proximal locations, high and low-familiarity groups showed opposite patterns with
38
39 respect to spatial congruency, consistent with the initial time data [$F(1, 39) = 13.915, p = .001,$
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41 $\text{MSE} = .410$]. Specifically, high-familiarity participants showed a larger AUC [$d = M_{\text{incongruent}} -$
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43 $M_{\text{congruent}} = .449, F(1, 39) = 4.92, p = .032$] on spatially incongruent trials, but low-familiarity
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45 participants showed a larger AUC [$d = M_{\text{incongruent}} - M_{\text{congruent}} = -.606, F(1, 39) = 9.41, p = .004$]
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47 on semantically incongruent trials (see Fig.5). Responses to distant locations showed no effects
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49 of familiarity or spatial congruency [$F(1, 39) = .143, p = .708, \text{MSE} = .547$].
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55 The analysis of PEP revealed a four-way interaction between familiarity, proximity, spatial
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57 congruency, and time bin [$F(4, 156) = 4.488, p = .002, \text{MSE} = .003$]. Consistent with the AUC
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4 results, responses to proximal trials showed an interaction between familiarity, spatial
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6 congruency and time bin [$F(4, 156) = 2.638, p = .036, \text{MSE} = .005$]; no such interaction was
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8 found with distant locations [$F(4, 156) = .084, p = .987, \text{MSE} = .004$]. To further understand the
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10 4-way interaction, we conducted a simple effects analysis examining proximal location data. The
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12 results of these analyses do not reach significance when accounting for multiple comparisons,
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14 but guide our interpretation of this complex and interesting interaction. The analysis suggests
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16 that low-familiarity participants had an interaction between spatial congruency and time bin [F
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18 (4, 156) = 2.63, $p = .037$], such that they moved closer to the opposite response on spatially
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20 congruent trials compared to spatially incongruent trials throughout time bins 2 [$F(1, 39) = 4.40,$
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22 $p = .042$], 3 [$F(1, 39) = 6.12, p = .018$], and 4 [$F(1, 39) = 5.22, p = .028$]. Put another way, low-
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24 familiarity participants moved closer to the opposite response on semantically incongruent
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26 compared to semantically congruent trials. While this interaction did not reach significance for
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28 high familiarity participants [$F(4, 156) = 1.52, p = .198$], the response pattern suggests that high-
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30 familiarity participants moved closer to the opposite response on spatially incongruent trials only
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32 late in their response, in time bins 4 [$F(1, 39) = 3.08, p = .087$] and 5 [$F(1, 39) = 5.25, p = .027$],
33
34 compared with mouse movement on spatially congruent trials. This interaction can best be seen
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36 in a graph of PEP difference scores (see Fig.6), computed by subtracting the PEP of spatially
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38 congruent trials from that of spatially incongruent ones. In the graph, positive scores mean
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40 mouse movements on spatially incongruent trials were closer toward the opposite response more
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42 than those on spatially congruent trials; negative scores mean mouse movements on spatially
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44 congruent trials were closer to the opposite response than those on spatially incongruent trials.
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46 Thus, negative scores reflect an effect of semantic congruency.
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57 *Accuracy and RT*
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4 Accuracy analyses indicated that incorrect descriptions trials showed a proximity effect [F
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7 (1, 39) = 7.863, $p = .008$, MSE = .020]. Opposite of the proximity effect with correct
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9 descriptions, participants made more errors with proximal [M = .720, SD = .148] than distant
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11 locations [M = .782, SD = .145]. In addition, high-familiarity participants [M = .788, SD = .131]
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13 responded more accurately (although not more quickly) than low-familiarity participants [M
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15 = .715, SD = .158, $F(1, 37) = 5.922$, $p = .020$, MSE = .036]. No other effects were found on RT
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17 or accuracy.
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20 21 **4. Discussion**

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23 The present study used a novel online processing measure, mouse tracking, to explore
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25 fundamental questions about spatial representations and their development. Participants with
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27 either extensive or more limited environment experience verified relative spatial locations using
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29 a computer mouse, and we tracked their movement trajectories towards a response. Results
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31 strongly suggest action-based compatibility effects (ACEs) when retrieving spatial information
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33 to verify spatial relations. These action-based influences appear to have distinct sources as a
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35 function of spatial representation development, being spatially driven with high-familiarity and
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37 semantically driven with low-familiarity. Additionally, spatial proximity, because of its
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39 implications for perceptual and motor interactions, also affected evidence of perceptuo-motor
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41 information retrieval.
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48 *4.1 Online Spatial Knowledge Processing*

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50 The present results suggest that spatial knowledge retrieval reactivates perceptual and
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52 motor experiences consistent with learning. As shown in Fig. 5, when correctly rejecting
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54 incorrect spatial descriptions of well-learned environments, participants with the NO button in
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56 the same direction as the relative spatial location (spatial congruent condition), mouse
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4 movements converged on this correct response, with little deviation in the opposite direction. For
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6 participants with the NO button in the opposite direction (spatially incongruent condition),
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8 mouse trajectories tended toward the opposite response. The initial time measure, while
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10 marginally significant, further suggested that high-familiarity participants might be more
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12 confident about their response on spatially congruent trials compared to the spatially incongruent
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14 ones (see Fig. 4). This finding is consistent with findings suggesting embodiment in language
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16 processing (Glenberg & Kaschak, 2002; Tucker & Ellis, 2004; Zwaan & Taylor, 2006) and
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18 extends to spatial knowledge retrieval.
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23 Many studies showing ACEs have explored language processing. From this work,
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25 Glenberg and Kaschak (2002) proposed a connection between language comprehension and
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27 motor processes. Other work has applied the ACE to visual processes, showing an interaction
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29 between current motor responses and visual stimulus position, named the *spatial stroop effect*
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31 (Lu & Proctor, 1995; Simon, 1990; Zhao, Chen & West, 2010; Zwaan & Taylor, 2006; Zwaan &
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33 Yaxley, 2003). For example, people respond more slowly when the visual target and response
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35 key are in opposite directions, even when target position is irrelevant to the required response.
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37 The present study extends the connection between cognitive and motor processing to spatial
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39 representations of environments. While response button positions in the present study did not
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41 directly relate to the spatial relationship judgments, the compatibility between the motor
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43 response and mental representation affected responses. Movements tended in a direction
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45 consistent with the relative spatial location, at least when rejecting incorrect spatial descriptions
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47 with well-developed spatial knowledge..
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54 55 *4.2 Embodied processing of Spatial Knowledge Development* 56 57 58 59 60 61

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4 The present study also explored how reactivation of perceptual and motor experiences may
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6 change as spatial representations develop. Interestingly, the mouse trajectory measure converged,
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8 strongly suggesting that the ACE has distinct sources at early and later stages of development
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10 (see Fig. 4-6). Incorrect spatial descriptions allowed us to disentangle spatial and semantic
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12 sources of motor resonance. Results showed that high-familiarity participants based judgments
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14 on stable spatial representations that associated landmarks to their own imagined location. In this
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16 case, mouse trajectories in spatially compatible trials moved more directly to the correct response,
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18 compared with those attracted by the incorrect response in spatial incompatible trials. In contrast,
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20 motor resonance for low-familiarity participants appeared to arise from associations to the spatial
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22 term (e.g., moving more left to the term *left*). Other studies have similarly shown that reading
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24 directional words activates corresponding perceptual or motor representations (Zwaan & Yaxley,
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26 2003; Hommel & Müsseler, 2006; Müsseler & Hommel, 1997a, b; Chao & Martin, 2000;
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28 Pulvermüller, 1999). In summary, retrieving information from well-learned environments leads
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30 to spatially-defined motor resonance while retrieving information from less-well-learned
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32 environments shows semantically-defined motor resonance.
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41 What stands out in our findings is that spatially-based motor resonance appears to eclipse
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43 its semantic-based counterpart for well-learned environments. With increasing environment
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45 experience, associations between spatial locations and navigators' sensorimotor processes
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47 become solidified and recalling relative spatial information then invokes motor resonance. Motor
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49 simulations based on well-developed spatial associations appear to "outweigh" associations to
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51 spatial terminology. In contrast, less-developed spatial representations have not built solid spatial
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53 associations, so motor resonance for these navigators is linked to the well-learned spatial terms
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55 ("left" or "right"). In summary, the present study indicates that with increasing experience
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4 human spatial knowledge builds associations between spatial locations that include perceptual
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6 and motor associations.
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8 9 *4.3 Temporal Dynamics of perceptuo-motor simulations*

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11 By using online measures, the present study revealed the temporal dynamics of perceptuo-
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13 motor associations when processing spatial knowledge. Our PEP measure to incorrect spatial
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15 descriptions suggested different temporal dynamics as a function of spatial knowledge
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17 development (see Fig.6). For low-familiarity participants, whose ACE appears semantically
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19 based, the ACE started early and extended throughout the response period. This suggests
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21 immediate and lasting motor resonance to spatial language. For high-familiarity participants,
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23 who showed spatially-based ACEs, effects of motor resonance appeared later. This later effect
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25 suggests that accessing spatial relation information takes longer than accessing a spatial term's
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27 semantic meaning. People would have had a lifetime of experience with the spatial terms and
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29 less so with the Tufts campus. In addition, Fig.6 (a) shows that mouse trajectories of high-
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31 familiarity participants gravitated toward the semantically congruent response at time bin 2,
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33 although the effect was not statistically significant. This weak effect may also support earlier
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35 semantic processing, even when retrieving well-developed spatial knowledge. But with well-
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37 learned environments, motor resonance based on semantic processing appears to be inhibited or
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39 attenuated.
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48 Previous studies showing ACEs in language comprehension primarily relied on post-
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50 processing response time measures (Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006).
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52 However, the present study's comparable measure did not show a congruency effect. Instead
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54 evidence of ACEs with spatial knowledge appeared in mouse trajectories. This post-
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56 processing/on-line processing difference has several possible explanations. One explanation
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4 involves strength of associations. Language processing, with all the experience participants have
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6 using language, may result in stronger and more lasting motor resonance that can be easily
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8 detected by post-processing measures. Compared to processing spatial terms, perceptuo-motor
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10 simulation activated when retrieving spatial knowledge may not have the same strength of
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12 association and may only be evident in online measures. Second, the different sources of
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14 perceptuo-motor associations, spatial and semantic, resulted in ACEs in opposite directions for
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16 incorrect spatial descriptions, thereby potentially washing out response time effects. Thus, mouse
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18 tracking may provide means for examining mechanisms of embodied processing masked by
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20 offline measures.
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25 26 *4.4 Spatial Proximity and ACE*

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28 As predicted perceptuo-motor associations varied as a function of spatial proximity:
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30 participants verified both proximal and distant locations. People would have more perceptual
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32 (see buildings together) and motor (point to one building from the other or turn the body to face
33
34 the building) experiences with proximal, compared to distant, locations. Thus, they are more
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36 likely to associate proximal locations using their body's coordinate axes (Franklin & Tversky;
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38 1990; Longo & Lourenco, 2007; Parsons, 1994; Witt et al, 2004). As Fig.3 illustrates, accuracy
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40 when processing correct spatial descriptions benefitted from spatial and semantic congruency for
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42 low-familiarity participants. With proximal locations, they had a higher accuracy in congruent
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44 condition, compared to incongruent condition, while no such facilitation of compatibility was
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46 found with distant locations. Further, the interaction between proximity, congruency, and
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48 familiarity when rejecting incorrect spatial descriptions suggested action compatibility primarily
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50 when processing proximal locations. No ACE was observed with distant locations, regardless of
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52 environmental experience. This result seems to contradict the semantic-based ACE for the low-
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4 familiarity group. If the ACE for low-familiarity participants arises from spatial term
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6 comprehension, then they should also demonstrate an ACE with distant locations. However, the
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8 lack or an ACE with distant locations may imply differential cognitive processing for proximal
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10 and distant spatial information. We did not observe an ACE for either high- or low-familiarity
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12 participants with distant locations when rejecting spatial relations. People may relate distant
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14 locations spatially, even during initial environment learning (Hölscher et al., 2011; Wiener &
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16 Mallot, 2003). Alternatively, people may create mental snapshots (Shelton & McNamara, 2001)
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18 that include proximal locations in a single mental image that maintains the relative locations, as
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20 well as perceptual and motor associations. Distant locations would be difficult to represent this
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22 way. In this case, ACE differences between proximal and distant locations would reflect
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24 differences in how they are represented, rather than effects of the learning experience. Previous
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26 findings from our lab suggest that a required retrieval perspective affects information retrieved
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28 from the spatial representation in a perspective-consistent manner (Brunyé, Mahoney, Gardony,
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30 & Taylor, 2010; Taylor et al., 1999). This interpretation would be akin to the SNARC effect
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32 (Dehaene, Bossini, & Giraux, 1993) wherein people represent Arabic numbers as if on a mental
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34 image of a number line. The consequence of this representation is that people respond faster to
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36 relatively larger numbers with the right hand, and faster to smaller numbers with the left hand,
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38 even when number magnitude is task-irrelevant. However, these interpretations are speculative
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40 and will be explored further in later studies.
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50 It should be noted that we did not observe the interaction between congruency and
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52 proximity when participants confirmed spatial relations. Instead, with correct spatial descriptions,
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54 participants' mouse trajectories showed a congruency effect, suggestive of embodiment, across
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56 proximal and distant locations (see Fig. 1 & 2). Thus, representations of distant locations may
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4 still involve some perceptuo-motor simulation. However, the source of this embodiment, whether
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6 spatial or semantic, cannot be disentangled and the ACE may reflect one or both of these sources.
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9 *4.5 Conclusion*

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11 To summarize, retrieving spatial knowledge of a well-learned environment appears to
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13 activate perceptual and motor simulations reflecting sensorimotor experiences when learning the
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15 environment. These simulations are built on dynamic association between navigator and
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17 landmarks formed during learning and increasing with environmental experience. With less
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19 experience, motor simulations draw on other, well-learned associations, in this case perceptuo-
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21 motor associations to spatial terms, such as *left*. By adopting on-line processing measures,
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23 findings from this study provide unique evidence of different sources for perceptuo-motor
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25 simulation in spatial memory, the effects of which unfold differently over time.
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Table 1 Means in correct description condition

Correct Description	Low-familiarity Group				High-familiarity group			
	Proximal		Distant		Proximal		Distant	
	Congruent	Incongruent	Congruent	Incongruent	Congruent	Incongruent	Congruent	Incongruent
RT	1766.046	1646.281	1827.827	1845.287	1810.225	1739.352	1905.826	1929.775
(SD)	502.098	441.298	483.122	520.160	583.283	465.255	678.410	764.034
Accuracy	0.824	0.752	0.705	0.719	0.815	0.835	0.845	0.815
(SD)	0.122	0.175	0.147	0.121	0.157	0.118	0.154	0.123
Initial time	365.987	348.747	415.820	356.074	487.527	417.546	494.213	590.825
(SD)	306.122	253.503	299.490	246.569	358.690	339.130	433.299	481.897
AUC	0.551	0.908	0.462	1.042	0.423	0.986	0.413	0.906
(SD)	0.431	0.590	0.370	0.740	0.488	0.861	0.514	0.609

Table 2 Means in incorrect description condition

Incorrect Description	Low-familiarity Group				High-familiarity group			
	Proximal		Distant		Proximal		Distant	
	Congruent	Incongruent	Congruent	Incongruent	Congruent	Incongruent	Congruent	Incongruent
RT	2076.999	1844.937	1891.292	1855.571	2020.678	2140.516	2034.185	2016.092
(SD)	480.330	521.658	620.449	540.701	570.174	723.145	638.187	666.236
Accuracy	0.648	0.714	0.757	0.743	0.765	0.755	0.815	0.815
(SD)	0.191	0.149	0.108	0.160	0.088	0.119	0.173	0.127
Initial time	465.400	353.512	458.303	408.728	534.087	642.871	528.692	560.709
(SD)	311.385	232.552	338.633	300.706	348.276	562.932	364.744	383.596
AUC	1.351	0.745	0.835	0.917	0.770	1.219	0.827	0.786
(SD)	0.897	0.620	0.792	0.846	0.915	1.200	0.741	0.806

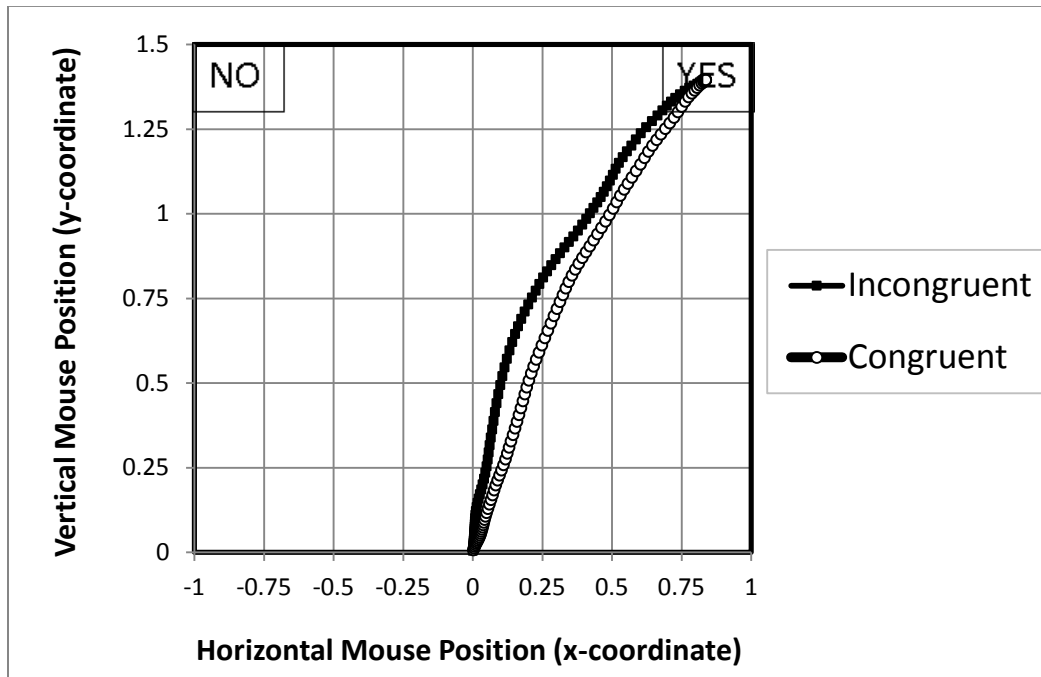


Figure 1. Main effect of congruency on real-time mouse trajectories during confirming correct descriptions. Mouse trajectories for incongruent trials gravitate in the direction defined by the spatial relationship and toward the incorrect response button. Note that mouse trajectories for participants with “YES” and “NO” buttons in opposite positions have been collapsed to the present position for ease of illustration.

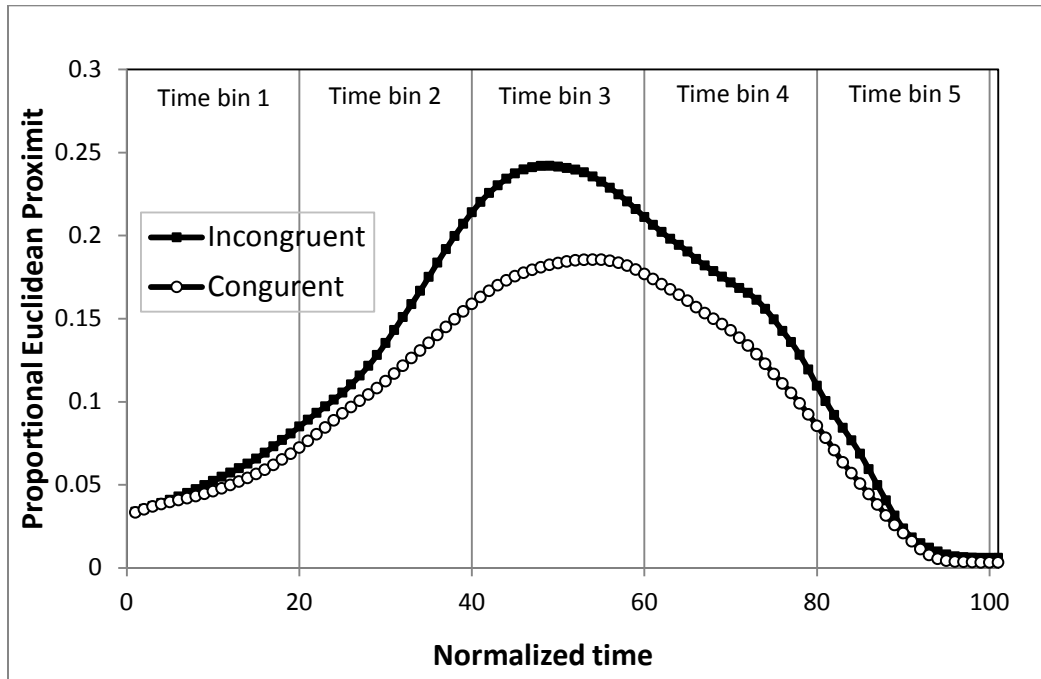


Figure 2. Interaction between congruency and time bin in proportional Euclidean proximity (PEP) for confirming correct descriptions. PEP was plotted as a function of normalized time. Mouse trajectories for incongruent trials show a greater attraction to the opposite response than do congruent trials, peaking during time bin 3.

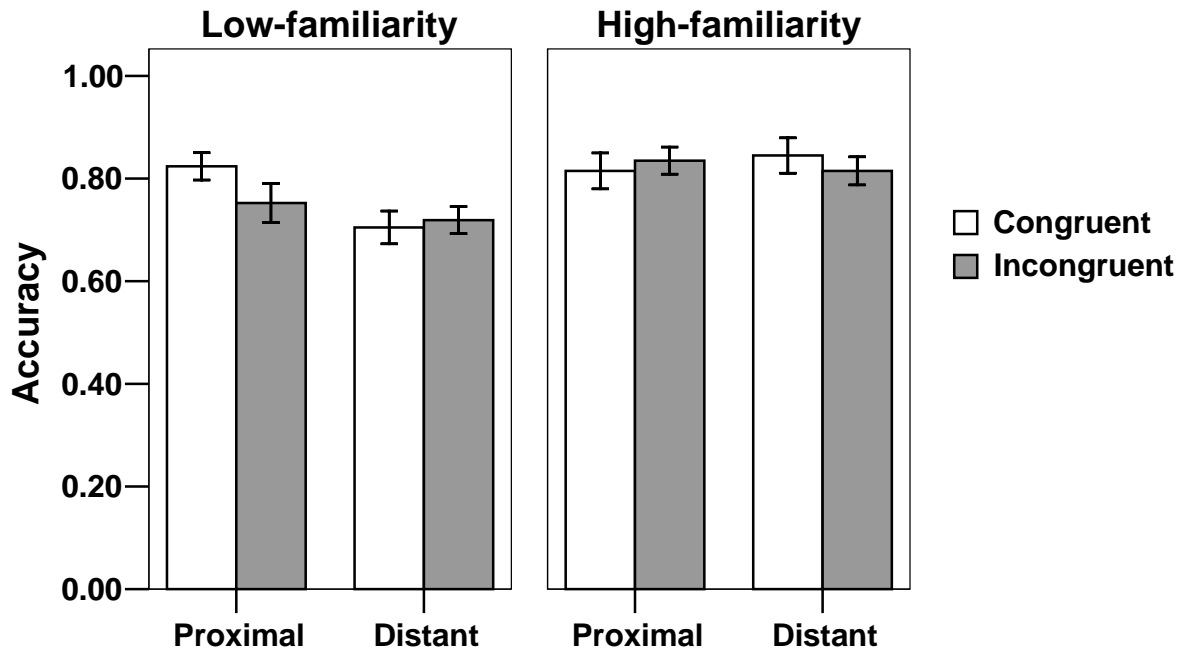


Figure 3. Three-way interaction between familiarity, proximity and congruency in accuracy of confirming correct descriptions.

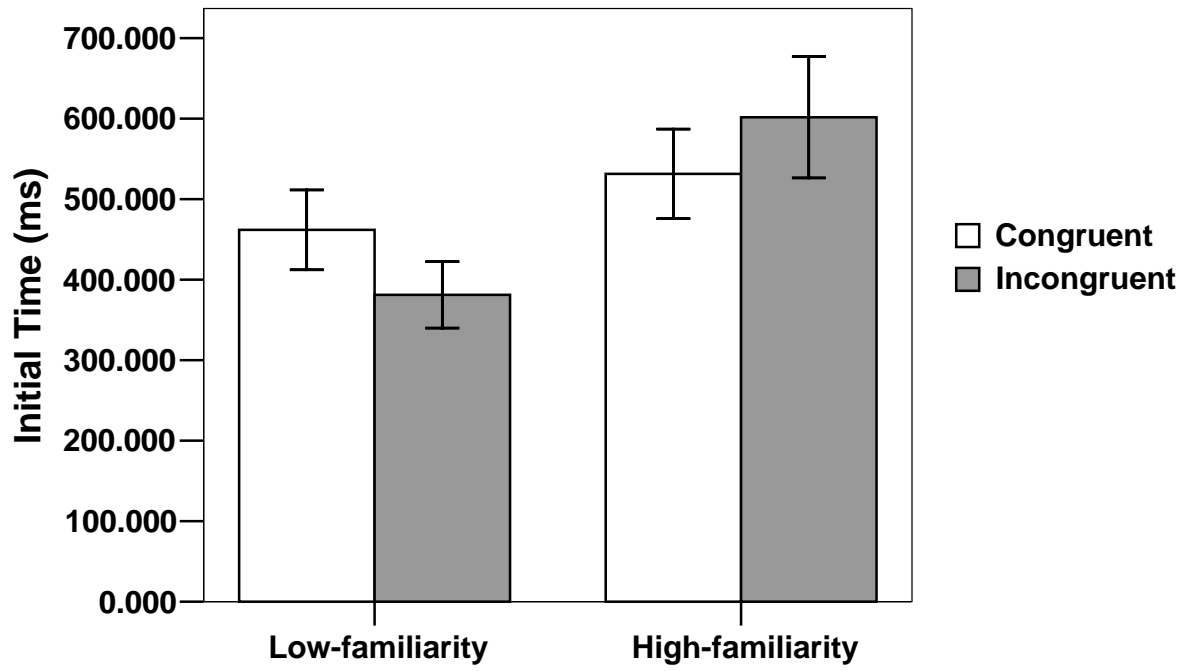
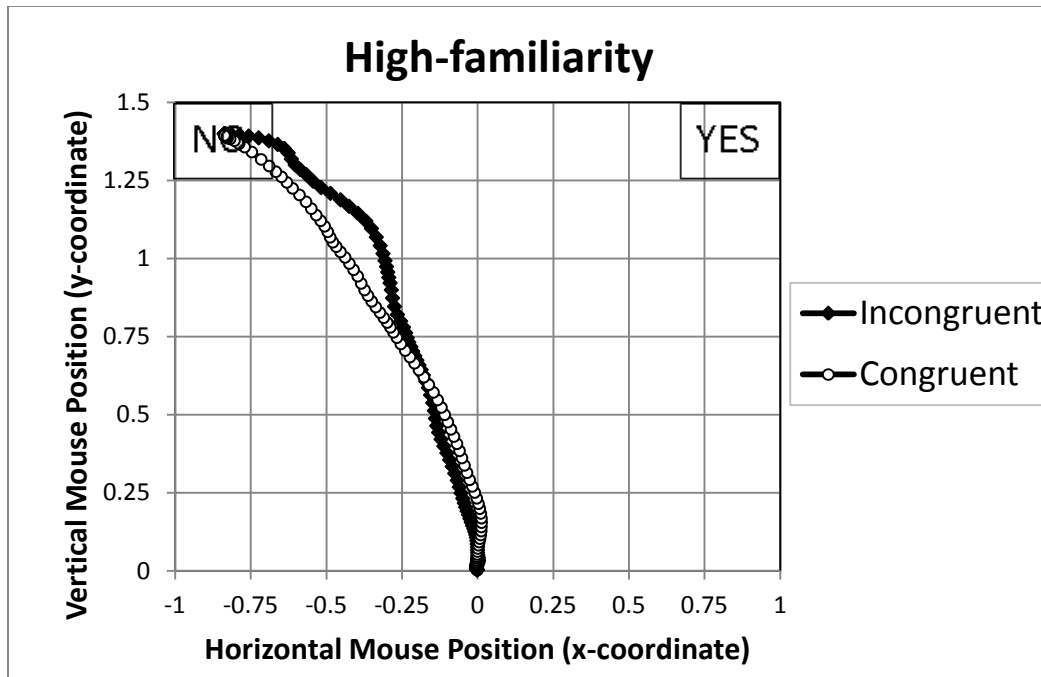
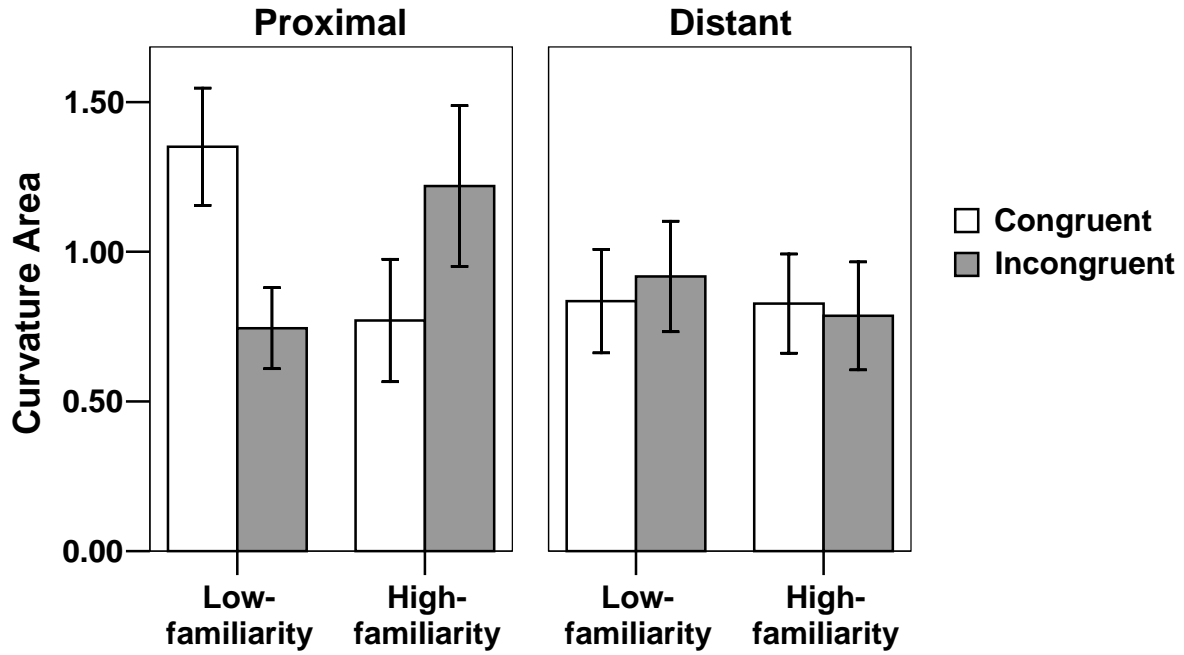


Figure.4 Interaction between familiarity and congruency in initial time of rejecting incorrect descriptions.



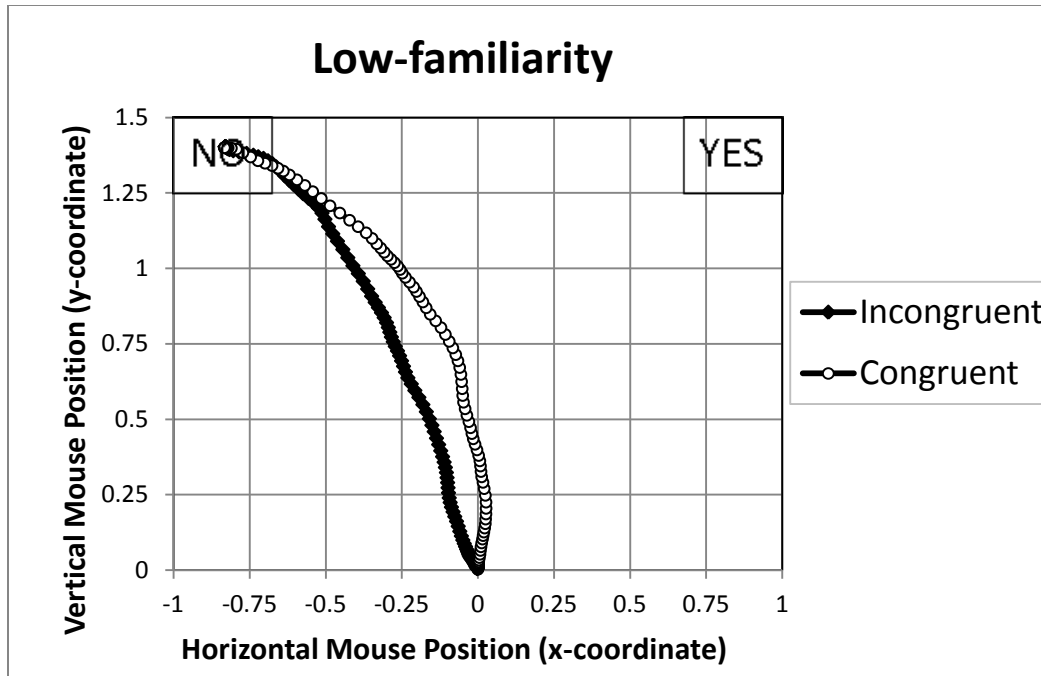


Figure 5. Three-way interaction between familiarity, proximity and congruency in AUC (a) of rejecting incorrect descriptions. Mouse trajectories for proximal trials help explain this interaction and are thus plotted as real-time figures: b) for high-familiarity group, mouse trajectories for incongruent trials show a continuous attraction to “Yes” response; b) for low-familiarity group, mouse trajectories for congruent trials show a continuous attraction to “Yes” response. Note that mouse trajectories for participants with “YES” and “NO” buttons in opposite positions have been collapsed to the present position for ease of illustration.

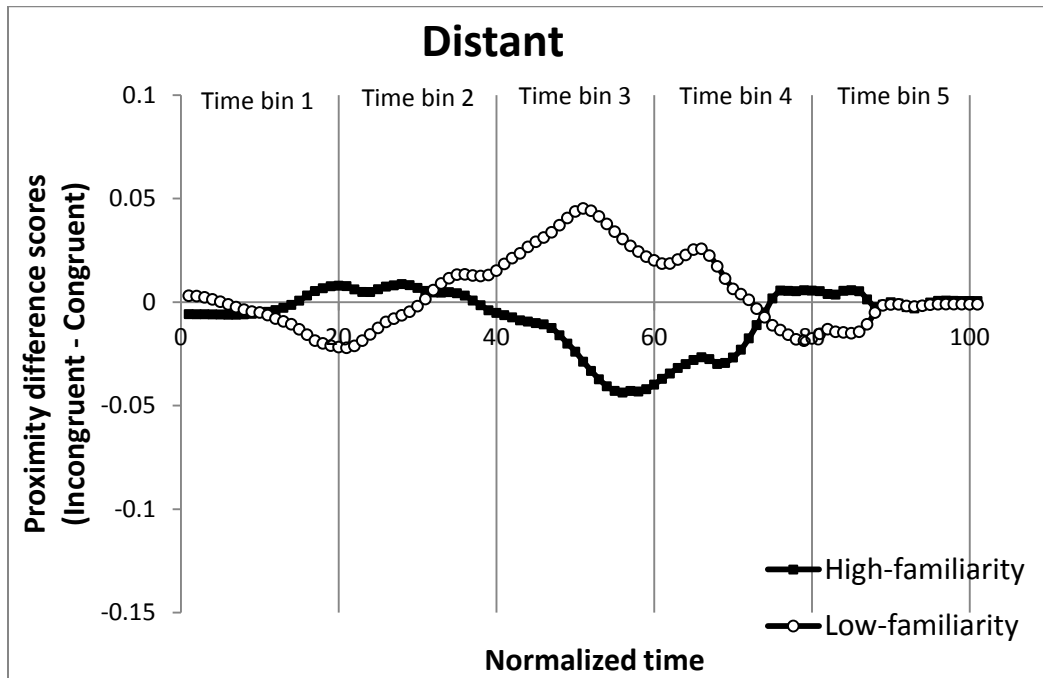
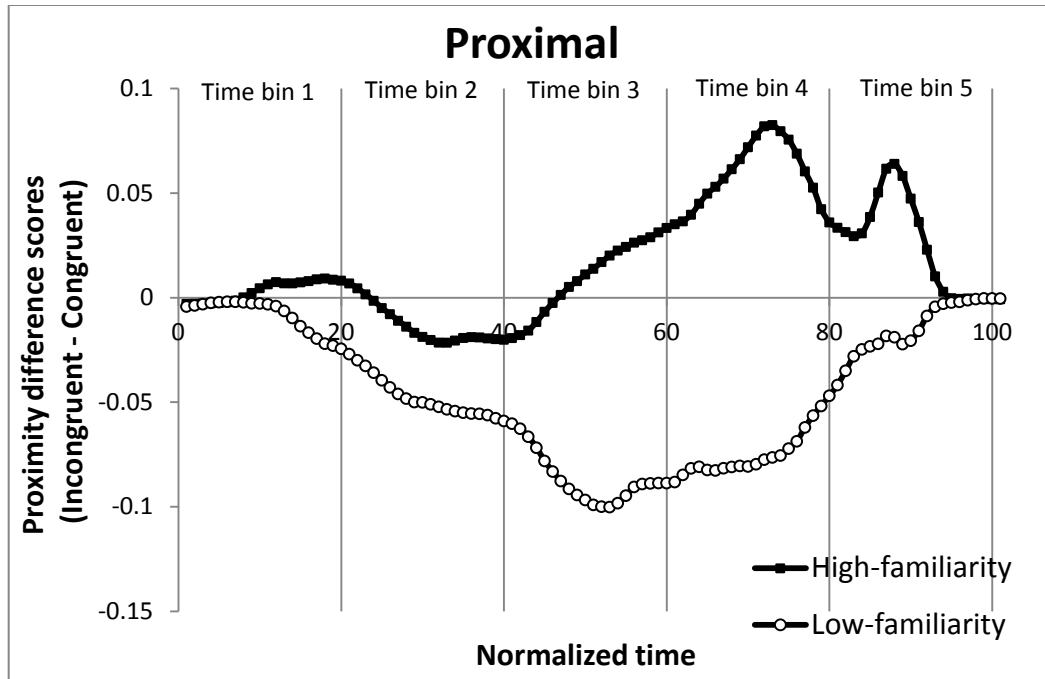


Figure 6. Difference scores between incongruent and congruent conditions (incongruent - congruent) in PEP for rejecting incorrect descriptions are plotted as a function of normalized time, separately for proximal (a) and distant (b) location pairs. For proximal trials (a), mouse trajectories of low-familiarity participants were closer to incorrect response in congruent condition throughout time-course (negative value), while those of high-familiarity participants were closer to incorrect response in incongruent condition at late stage of mouse movement (positive value).

When Going the Right Way is Hard to do:

Distinct Phases of Action Compatibility in Spatial Knowledge Development

Abstract

The present study explores spatial knowledge development using online response measures available in mouse tracking. Online measures can reveal cognitive processing masked in post-processing measures. In the study, participants verified spatial descriptions by moving the mouse to a YES or NO button. Mouse tracking software (Freeman & Ambady, 2010) recorded mouse trajectories. Results demonstrated action-compatibility effects (ACE), differing as a function of spatial knowledge development. For well-developed spatial knowledge, the ACE reflected the physical spatial relationship (e.g. response button on right, but building to the left). In terms of temporal dynamics, this effect occurred later in the response. For less-developed knowledge, the spatial term drove the ACE (e.g., response button on right, but description used term *left*). In this case, the ACE was immediate and continuous. As would be consistent with learning, ACEs were observed more probably with proximal than distant locations. From these results, we infer that perceptuo-motor associations build with time and experience and can play an integral role in retrieval from well-developed spatial representations.