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Abstract

Humans do not learn spatial layouts by making detailed mental snapshots. In contrast, they organize and integrate the available information into dynamic cognitive structures. Indeed, there is evidence that sensory information undergoes considerable change on its way from the eye, ear, and other receptors to perceptual systems and memory. To account for a number of these changes, we present a theoretical framework based on the Theory of Event Coding (Hommel, Müsseler, Aschersleben & Prinz, 2001). We suggest that spatial maps consist of integrated event files or object-action complexes that include information about the features of objects of a layout and the actions these objects afford. We demonstrate how this framework explains available experimental effects and discuss further implications.

Introduction

Everyday behavior is often guided by cognitive representations of our spatial environment. These representations are necessary to plan the most efficient route from one location to another and find our way to the fridge at night. This suggests that representations of objects are integrated with information about where those objects are located, so that accessing an object representation also provides cues about where to find that object (e.g., consider the transition from landmark via route to survey knowledge, Siegel & White, 1975). However, as we will argue below, there is increasing evidence that objects are also integrated with information about the actions they afford (Gibson, 1979). This suggests that cognitive maps do not only consist of object representations but, rather, of spatially structured object-action complexes or event files (Hommel, 2004; Hommel, Müsseler, Aschersleben & Prinz, 2001). In other words, cognitive maps can be seen as spatially structured embodied action opportunities. Here we develop this line of thought by reviewing and integrating recent studies from our lab, suggesting a biologically plausible theoretical framework of how the elements of spatial maps are cognitively represented, and explaining how this type of representation affects the speed of access to the individual elements of a map.*

Object Files

If people interact with spatial layouts of objects, they build up internal representations that, in one way or another, keep information about the spatial relations between those objects. Interestingly, however, the spatial information undergoes considerable changes on its way from the sensory surface to memory, which sometimes even involves systematic distortions of the original information (for overviews see Friedman et al., 2002; McNamara, 1991; Tversky, 1981). These changes are likely to reflect the way the incoming information is organized by the cognitive system, suggesting that studying those changes reveals the logic according to which the organizational processes operate.

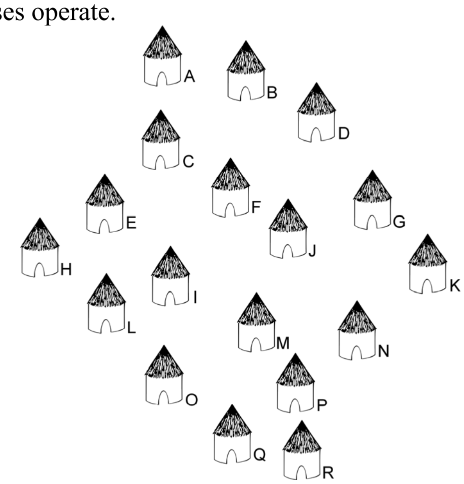

Figure 1. Schematic graph of the layout used by Hommel, Gehrke, and Knuf (2000). The letters indicating the locations were not shown; instead each hut was identified by a nonsense name (i.e., a meaningless syllable like "MAW", omitted here) appearing in its center (see Figure 2).

Our own research began with the question whether organization-induced changes in the accessibility of elements of spatial maps result from perceptual or memory processes. In the literature, distortions of spatial information have been often attributed to memory processes, such as the encoding of spatial information (e.g., McNamara & LeSueur, 1989), its retrieval (e.g., Sadalla,

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Staplin, & Burroughs, 1979), or both (Tversky, 1991). However, our own findings suggested a perceptual locus.

In the study of Hommel, Gehrke, and Knuf (2000) subjects faced a map-like configuration of 18 objects, which looked like huts of an imaginary village (see Figure 1). The huts had individual names (nonsense syllables [in German], like DUS, FAY, or MOB; see Figure 1) and were colored in such a way that the configuration was subdivided into three or four perceptual groups (e.g., huts at locations B, C, D, and F were red, huts at locations E, H, I, and L green, etc.). Subjects estimated Euclidean distances between huts and verified sentences describing spatial relations (e.g., "is MOB above FAY?") in a perception session, where the configuration was constantly visible, a memory session, where the configuration was first memorized and then deleted from the screen; and a final perception/memory session, where the configuration was again visible during the tasks. Whereas no systematic effects were observed in distance estimations, subjects were faster to verify the spatial relation between huts of the same color than between huts of different colors. The same outcome was obtained when the huts were all of the same color but differed in form, hence, relations between same-form pairs were verified faster than relations between different-form pairs.

Interestingly, this was true for all three sessions, which indicates that memory processes were unlikely to be responsible. Apparently, the access to both perceptual and memory representations of two given objects is facilitated if they share a perceptual feature and, thus, belong to the same perceptual group. Comparable benefits of judging objects sharing one or more perceptual or semantic feature have been observed by others in both perceptual (Baylis & Driver, 1993) and memory studies (e.g., Maki, 1981; McNamara, Ratcliff, & McKoon, 1984; Stevens & Coupe, 1978; for an overview, see Gehrke & Hommel, 1998).

A tenable account of this phenomenon is sketched in Figure 2 (cf., Hommel & Knuf, 2000). Imagine you are facing three huts, ordered from left to right and named DUS, FAY, and MOB, with DUS and FAY shown in green and MOB in red. If we assume that object representations are integrated bindings of perceptually derived feature codes (*object files*: Hommel, 2004; Hommel et al., 2000; Kahneman, Treisman, & Gibbs, 1992), the three huts might be represented as shown in the (extremely simplified) figure (ignore the action map for a moment). For instance, the representation of DUS might include a name code (DUS), a spatial code (left) and a color code (green), plus some more codes (not shown) referring to shape, texture, and so on; the same logic holds for the representations of FAY and MOB. According to this scheme some feature codes would be shared by all representations (e.g., those referring to shape and texture) and some other codes would not be shared (the name codes). Importantly, however, there is one code in our example that is shared by two of the objects (DUS and FAY), thereby creating what one may call a representational subcluster. Given that the members of a subcluster are structurally connected, accessing one member also activates the other members to some degree (that depends on the amount of code overlap). If we therefore assume that accessing and comparing objects whose representations overlap is easier than comparing objects that do not, it becomes clear why Hommel et al. (2000) obtained faster verification responses for objects of the same color or of the same shape. Note that this account predicts *quicker access* to feature-overlapping object representations for spatial (and other) judgments but not (necessarily) *higher accuracy* or validity of the accessed information. This fits well with Hommel et al.'s finding that feature overlap affects the speed of spatial verification judgments but not the accuracy of (unspeeded) distance estimations.

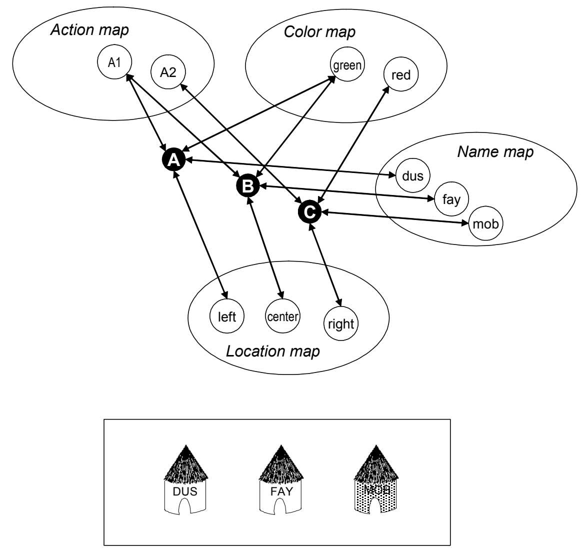

Figure 2. A model of the impact of nonspatial information on the verification of spatial propositions. The green stimulus huts DUS and FAY, and the red hut MOB are cognitively represented by integrated object features referring to the object's name, location, color, etc, and converging on a common node (A, B, and C, respectively). Note that the representations of DUS and FAY overlap, so that accessing DUS primes FAY, and vice versa. Moreover, DUS and FAY are associated with the same action (A1), while MOB is associated with another action (A2).

Object-Action Complexes

The idea that object representations consist of bindings between codes representing perceptual features is rather uncontroversial. However, there is also increasing evidence that information about objects is integrated with information about the action an object affords. For instance, Merril and Baird (1987) had students sort names of familiar local campus buildings. Based on a cluster analysis two sorting criteria were identified: the spatial proximity between the buildings and their (shared) function, i.e. all the dormitories, fraternities, and classrooms were sorted together. Inasmuch as sorting behavior can be taken to indicate memory organization, this organization seems to reflect action-related characteristics of the map elements. In another study, Richardson and Spivey (2000) presented subjects with short video clips, each one at a different location, showing a speaker reading facts about a particular city. When subjects were later asked questions about those facts, they tended to look at the (now blank) location where the fact had been presented, but only if they had fixated this location already during fact presentation. This suggests that looking at a particular event leads to some kind of integration of the looking behavior and the event it aimed at. In a study of Carlson-Radvansky, Covey, and Lattanzi (1999) subjects placed pictures of objects "above" or "below" a reference object. The functional relatedness between the two objects could be high, such as when a toothpaste tube was to be placed above or below a toothbrush, or low, such as when a tube of oil paint was to be placed above or below a toothbrush. When the reference object was presented in an asymmetrical fashion (e.g., a toothbrush with bristles at one end of the brush), the horizontal placement was found to be biased towards the "functional parts" of the reference object (e.g., the toothpaste tube was placed closer to the bristles), and this bias was more pronounced with functionally related object pairs. As object functions were irrelevant in Carlson-Radvansky et al.'s task, this observation suggests that functional, action-related information is an integral part of object representations.

According to the Action-Concept Model of Hommel (1997) and the more comprehensive Theory of Event Coding (Hommel et al., 2001) actions are cognitively represented by codes of the features of their sensory effects, that is, by representations of the perceptual events the particular action is known to produce (Elsner & Hommel, 2001). Given that action effects are not qualitatively different from any other perceptual event, it makes sense to assume that the codes of the effects of an action become linked to the codes of the objects this action commonly aims at. In other words, objects and actions should be integrated into event files (Hommel, 2004) or object-action complexes. Figure 2 shows a prediction that can be derived from this consideration. Imagine that our three huts no longer differed in color but had been associated with particular actions, say, A1 (DUS and FAY) and A2 (MOB). Accordingly, color no longer discriminates between the elements of the map (even though the green color is of course still coded) but the representations of the huts DUS and FAY are indirectly linked by sharing the same action. If so, we would predict that spatial relations between objects that are associated with the same action should be easier to assess than relations between objects associated with different actions.

Experiments

We conducted 3 Experiments that tested this prediction (a full description of the method can be found at www.personal.psu.edu/auk23).

Experiment 1

Experiment 1 tested the central hypothesis that associating elements of map-like configurations with particular actions would lead to the cognitive clustering of their representations. We used the same layout as Hommel et al. (2000), except that all houses were of the same color and shape. First subjects learned to associate each house with a particular keypressing action (except for the filler houses in locations A and R). Between four and six houses were mapped onto the same key. After having figured out and acquired the valid house-key mappings, subjects verified sentences about spatial relations between houses, just like in the Hommel et al. study. They carried out these tasks two times, first in front of the visual display (the perception session) and then, after having memorized the spatial layout, from memory (the memory session).

Results. Error rates were below 2% and the respective trials were excluded from analysis. In an ANOVA with the factors session (or condition) and action-group membership the main effect of session, $F(1,20)=30.96$, $p<.001$ was highly significant, indicating that reaction times decreased over sessions (4093 vs. 2945 ms). Group membership clearly failed to reach significance level, $F(1,20)<1$, while the interaction with session approached significance, $F(1,20)=3.26$, $p=.08$. Yet, even the latter effect did not meet the expectations: If anything, verification times in the perceptual condition tended to be faster for pairs assigned to different keys than to the same key.

Discussion. We assumed that action-related associations of elements of a spatial map would lead to a cognitively structured organization of the spatial information, which should lead to faster access to objects associated with the same action. However, the results do not confirm the predicted clustering effect. In contrast to previous experiments showing color- and form-related clustering effects, action did not seem to produce any effect (memory condition) or, if any, a trend in the wrong direction (perceptual condition). We could imagine at least two, non-exclusive reasons for why our predictions might have failed in this experiment (apart from the possibility that they are incorrect). One is related to the possible decay of mapping information and will be tested in Experiment 2; the other is related to the (lack of) strength of house-action associations and will be investigated in Experiment 3.

Experiment 2

A possible reason for why no clustering effects were obtained in Experiment 1 might be the quick decay of associations between house representations and actions. According to this decay hypothesis, it may very well be that the representations of our house-like objects became associated with the assigned keypressing action, thereby integrating the actions into the object representations. However, after the mapping-induction phase neither the actions nor their assignment to houses were any more relevant, so that the activation of response codes and/or the house-key associations may have decayed. If so, the representations of houses assigned to the same response may have still been connected through the overlapping action code, but activation spreading along this route may have been too weak to produce an effect. Hence, we should be able to find a clustering effect (i.e., faster verification for same-action pairs) if we prevented decay of information about the house-key mapping. This was the rationale for designing Experiment 2, which for the most part was a replication of Experiment 1. However, to prevent mapping information from decaying, location-response associations were reactivated at the beginning of each task by having the subjects repeat the stimulus-response task used to introduce the mapping in the first place.

Results. The overall error rate was 3.5% and all error trials were excluded from analysis. The factors session, $F(1,22)=18.49$, $p<.001$, and group membership, $F(1,22)=24.68$, $p<.001$, yielded main effects but they did not interact, $F(1,22)<1$. Faster reaction times were obtained for pairs assigned to the same action (3144 ms) than for pairs assigned to different actions (3517 ms), and reaction times decreased over sessions (3676 vs. 2986 ms).

Discussion. The outcome of Experiment 2 is clear-cut. Repeatedly reminding our subjects of the house-key mapping rules before estimating distances and verifying spatial relations did indeed produce the predicted clustering effects in both sessions. As introducing these mapping reminders was the only modification to Experiment 1, which did not produce the expected outcome, we can conclude that the reminders were effective in enforcing an "update" or "refresh" of the mapping rules. Apparently, this update worked against the decay of those rules, so that they could mediate the spreading of activation between the representations of houses associated with the same action. Consequently, accessing house representations to extract spatial information for the verification task primed codes representing the associated keypressing action which, in turn, must have primed house representations associated with them.

Experiment 3

In interpreting the negative outcome of Experiment 1 we considered the semantic relationship between stimuli and responses a possibly important factor. Given the positive result of Experiment 2 we can rule out that semantic relations are necessary to create clustering effects, but it may well be possible that more meaningful relations produce more robust effects. In Experiment 3 we used a similar design as in Experiment 1 (i.e., without mapping reminders) but instead of arbitrary keypressing actions we employed actions that were semantically related to houses, such as opening the door of a toy house or operating a door knocker. If preexisting, semantic stimulus-response relations make it easier to integrate action codes into the cognitive representations of the houses of our visual city, we would expect clustering effects in verification times, just as in Experiment 2, even in the absence of mapping reminders. However, it is obvious that this new set of actions is not only more house-related than the old set of Experiments 1 and 2 but also more complex. Yet, apart from any semantic relationship complexity as such may facilitate the retrieval or reactivation of integrated action codes—simply because more complex actions have more features and are therefore represented by more codes that might function to connect object representations. To see whether complexity alone would be able to produce reliable clustering effects we decided to run a second group of subjects with complex actions lacking any obvious semantic relationship to houses.

Results. Error rates were below 3% and the respective trials were excluded from analysis. An ANOVA with the factors condition (perception vs. memory), semantic relation (house-related vs. unrelated) and group membership (within-group vs. between-group) yielded a highly significant main effect of condition, $F(1,19)=13.75$, $p<.001$, indicating that responses were faster in the memory condition than in the perception condition (3216 vs. 3879 ms). The second source of variance was a highly significant main effect of action-group membership, $F(1,19)=14.61$, $p<.001$. Spatial judgments were faster for pairs assigned to the same action than for pairs assigned to different actions (3379 ms vs. 3715 ms). This effect was modified by a marginally significant group membership x semantic relation interaction, $F(1,19)=4.11$, $p=.057$. As revealed by separate t-tests, this was due to that the effect of group membership was reliable only in the “house-related action” group (3231 vs. 3732 ms), $t(10)=4.14$, $p<0.001$, always one-tailed. Results in the “house-unrelated action” group pointed in the same direction (3542 ms vs. 3696 ms) but did not reach significance, $t(9)=1.28$, $p=0.117$.

Discussion. Experiment 3 investigated the role of the semantic relationship between stimuli and responses with respect to the integration of action-related information into a spatial object representation. Although no mapping reminders were used, reliable clustering effects were obtained under perception and memory conditions—exactly as predicted. This shows that no extra activation of mapping rules is needed for complex, semantically related actions to mediate cognitive clustering of objects, suggesting that the underlying associations between house representations and codes of the assigned action are stronger and/or more active than those related to the arbitrary keypressing actions used in Experiment 1. However, even though there was some evidence that semantically unrelated actions produced a numerically much smaller and statistically less reliable effect than house-related actions, the unrelated actions did seem to be more effective than the simple key presses in Experiment 1. This suggests that complexity as such might help to produce clustering, although not as strongly as the combination of complexity and semantic relatedness. Taken altogether, the three experiments provide strong support for the assumption that actions contribute to the structuring of spatial maps.

Aspect Integration

The elements of maps can be characterized by their features or aspects (e.g., Berendt et al. 1998, Klippel et al., 2005). Depending on the current situation and the action goal of the given individual, different features or aspects of the elements are relevant. For instance, when looking for a particular address, the spatial proximity of houses is relevant: if I'm looking for number 15, houses with numbers between 1 and 31 are more relevant (as cues to the actual target) than are houses with numbers between 101 and 131. However, if I'm willing to post my mail, the function of houses is more relevant: everything looking like a post office is interesting. Thus, different actions and action goals call for the emphasis of different aspects (Berendt et al., 1998). How are such different aspects acquired? One possibility is that different maps are created for different aspects, so that people can switch between maps if they are changing their goals. Alternatively, people may integrate all information available into the same map (McNamara & LeSueur, 1989) and dynamically weight the contribution from the various feature maps in a goal-specific fashion (Hommel et al., 2001; Memelink & Hommel, 2006).

A recent study suggests that the latter option is more plausible. Hommel and Knuf (2003) presented subjects with the same map-like configurations as shown in Figure 1 and manipulated the similarity between the features of the map elements and of the actions associated with them. As observed previously, spatial comparisons between elements were carried out faster if the elements were presented in the same color or if they were associated with the same action. In the next session, subjects were presented with the same configuration but now the colors or actions could be changed. For instance, some subjects first saw two given huts in the same color (say, DUS and FAY) and another hut in another color (MOB). In the next session, these subjects learned to associate each hut with a particular action. Some of these associations were compatible with the previous similarity relationship (e.g., if DUS and FAY were associated with one action and MOB with another). Other associations were incompatible (e.g., if DUS was associated with one keypress and FAY and MOB with another). The question was whether compatibility with the previous similarity relations matters. If people would store different maps for each session, this should not be the case. However, if people would integrate color, action, and location into the same object-action complex, one would expect that previously experienced relations would still affect behavior. Indeed, comparisons of elements that had a compatible relationship in the previous session were faster than comparisons of elements with incompatible relationships. Thus, all the information about a given object or event seems to be integrated into one coherent representation--at least in a functional sense.

Prospects

The available evidence suggests that spatial maps consist of event files or object-action complexes, that is, of integrated bindings of information about the features of objects and the actions they afford. The contribution of this information to action control in a particular situation depends on the acting person's current goals, in the sense that goal-related feature dimensions and action affordances are more strongly weighted. This theoretical framework has quite a number of interesting implications. In general, it suggests that cognitive systems are made of integrated sensorimotor units rather than input codes that are translated into output codes. That is, adaptive behavior emerges from the continuous interaction of perception and action—an insight that is only beginning to impact our thinking about cognition in biological (Hommel et al., 2001) and artificial agents (http://www.paco-plus.org). But there are also more specific implications. For instance, object-action complexes are likely to integrate information from several sensory modalities, suggesting that the maps they are involved in can be considered multimodal spatial representations. Furthermore, object-action complexes do not only seem to integrate "cognitive" information about features and affordances but also affective information specifying the feelings the given object or action has been associated with in the past (Hommel, 2006; Lavender & Hommel, in press). This raises the possibility that emotions contribute to the organization of spatial and spatially structured information, so that the reward-punishment history of a person can color his or her spatial maps (e.g., somatically marked "no-go area”). Another implication is that the cognitive organization of spatial configurations is likely to undergo continuous individual change. For instance, if someone moves to a new city, she will start exploring parts of it by means of a particular transportation medium, be it by bus, bike, car or feet. The medium chosen is likely to determine the organization of the acquired map, so that easy to reach places will become stronger cognitively connected than difficult to reach places–independent of the Euclidian distance of these places (McNamara et al., 1984). However, switching to another medium (from bike to car, say) is likely to change this organization, because some places are easy to reach by bike but difficult to reach by car, and vice versa. Using the subway is likely to induce further changes, and so on. Likewise, the explorer’s emotional state will direct her attention to specific objects that will serve as anchor points (Couclelis, Golledge & Tobler, 1987) for her cognitive maps as well as for specific actions influencing her route knowledge, i.e. how to get from A to B (or to the fridge). Hence, cognitive maps are always in motion.

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