Qualitative modeling of spatial orientation processes using a logical network of necessary and sufficient conditions.

MAX-PLANCK-GESELLSCHAFT

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MPI FOR BIOLOGICAL CYBERNETICS

• Abstract

Goal: Model spatial orientation processes

Approach: Analyze logical relations

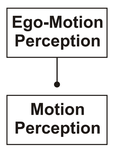
Results: Framework of necessary and sufficient conditions for spatial orientation

In this paper, we attempt to model spatial orientation processes by analyzing their logical and functional relations. This leads to a network of necessary prerequisites and sufficient conditions for spatial orientation, spatial presence, and spatial updating. More specifically, the logical structure of the framework allows to clearly disambiguate between complementary spatial orientation processes like continuous vs. instantaneous spatial updating. The framework proved especially well-suited for analyzing situations where certain processes related to spatial orientation were impaired, as is often the case in Virtual Reality applications. It further enables us to derive new hypotheses and testable predictions

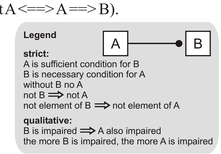
• Introduction

Findings from spatial orientation and navigation experiments are typically rather diverse and highly task-dependent. In this paper, we attempted to model the underlying spatial orientation processes by analyzing their logical and functional relations. This eventually led to a network of necessary prerequisites and sufficient conditions for spatial orientation, spatial presence, and spatial updating.

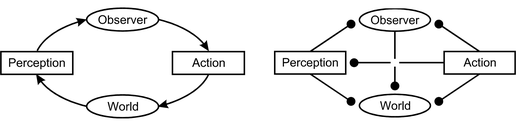
• Logical Modeling



How does logical modeling work? For example, it is evident that ego-motion perception cannot occur without some kind of motion perception or sensation. That is, intact ego-motion perception seems to logically depend on intact motion perception (NO motion perception ==> NO ego-motion perception). Conversely, if we observe intact ego-motion perception, we can conclude that motion perception must also be intact, which can be represented as ego-motion perception ==> motion perception (as not B ==> not A <==> A ==> B).



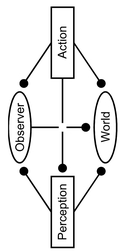
Information flow vs. logical representation of perception-action loop



(a) Information flow representation (b) Logical connectors representation

Figure 2: Perception-action loop, adapted to illustrate the difference between the typically used information flow arrows and our logical connections. (a) In the information flow paradigm, the observer obtains information about the surrounding world though perception. At the same time, the world is influenced by and receives information about the observer through her/his actions. (b) Using logical notations, the graphic looks quite different: The world at the bottom is the necessary prerequisite for the observer as well as her/his action and perception, indicated by the logical connectors ending at the world box. The opposite is true for the action box: All connections to it start there, indicating that any meaningful action requires an observer that is acting, a world (s)he is acting upon, and perception of the world, or else the behavior would be at random. Last but not least, perception implies and logically requires some perceiving entity, represented here as the observer.

• Overview of the Model



Spatial behavior and spatial perception are the main components of the perception-action cycle and constitute the top and bottom part of the framework, respectively (see Figures to the left and below). Meaningful spatial behavior is essentially based and logically dependent on spatial perception, and is mediated by several possible spatial orientation processes.

At the bottom part of the framework, we distinguish mainly between two branches, a relative motion branch on the left side and an absolute location branch on the right side (see Figure below).

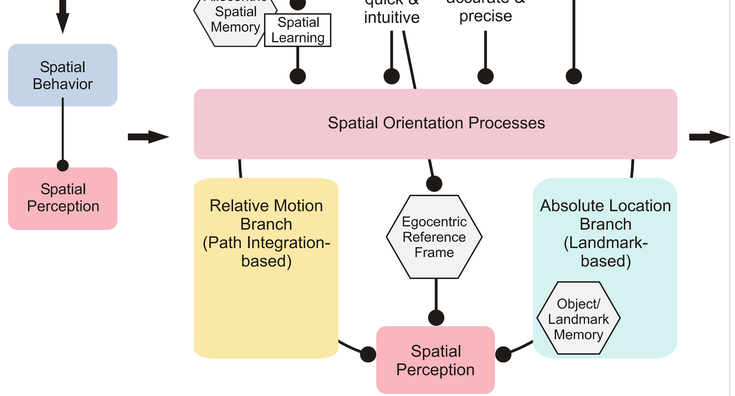


Figure 2: Overview of logical model

2 main branches: relative motion branch vs. absolute location branch

The left "**relative motion branch**" is based on path integration of perceived motions. It is responsible for generating the perception of ego-motion (e.g., vection) and the continuous updating of the self-location in space.

The right "**absolute location branch**" constitutes an alternative approach to finding ones way around, by using landmarks as reference points. Object/landmark memory is hereby involved in the recognition of salient features in the environment.

Spatial updating as necessary prerequisite for robust & automated spatial orientation

In addition to the left and right branch, we propose a third pathway that is responsible for robust and automated spatial orientation. That is, if we want to know where we are without having to think much about it, we need some process that allows for quick & intuitive spatial orientation and prevents us from getting lost, even when we do not constantly pay attention. To achieve this, some automated process (called "**automatic spatial updating**" or just "spatial updating") needs to always update our egocentric mental reference frame of the surround during ego-motions, such that it stays in close alignment with the physical surround.

4 qualitatively different aspects of spatial orientation:

4 underlying spatial orientation processes:

We distinguished between four qualitatively different aspects or properties of **spatial orientation processes**: **adaptable**, **quick & intuitive**, **accurate & precise**, and **abstract strategies.** These different aspects of spatial behavior seem to depend logically on different underlying spatial orientation processes and data structures. We categorized those processes into **cognition** (abstract mental reasoning), **piloting** (landmark-based navigation), **continuous spatial updating** and **instantaneous spatial updating**. The complete framework is presented in Figure 3 for reference. Instead of trying to explain the whole framework, we would instead like to focus here on the two spatial updating processes that are responsible for robust and effortless spatial orientation.

• Full Model

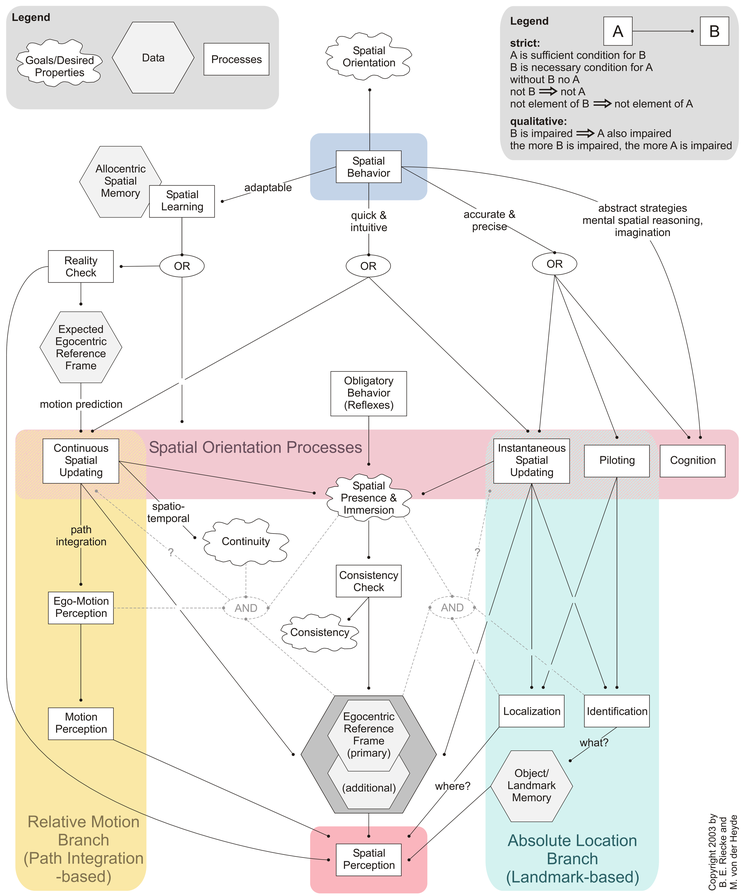


Figure 3: Full logical model

• Continuous vs. Instantaneous Spatial Updating

"Continuous spatial updating" for incremental transformation of egocentric reference frame

"Instantaneous spatial updating" for automatic re-orientation of egocentric reference frame

"Continuous spatial updating" refers to the largely automated and reflex-like process of updating our mental egocentric reference frame during self-motions based on continuous motion cues. Continuous spatial updating is based on the integration of the perceived ego-motion, whereas instantaneous spatial updating is based on object and scene recognition (see Figure 3). "Instantaneous spatial updating" occurs for example in the moment of waking up after having fallen asleep on a bus: As soon as we look out of the window and recognize the outside scene, we are automatically re-anchored to that reference frame. That is, we immediately know where we are without any conscious effort and without being able to suppress that re-anchoring (instantaneous spatial updating) of our egocentric reference frame.

• Continuous vs. Instantaneous Spatial Updating

At least one spatial updating process is required for quick&intuitive spatial orientation

Only instantaneous spatial updating allows for re-orientation

First test of the model were successful

Distinguishing between continuous and instantaneous spatial updating proved useful

Embedding these two spatial updating processes into a framework of logical connections allows to clearly disambiguate between them: Either of these processes may enable (i.e., is a logical prerequisite for) quick & intuitive spatial orientation (see Figure 3). Only instantaneous spatial updating, however, allows for accurate & precise spatial orientation, as it is based on the localization and identification of landmarks embedded into a consistent scene. This has specific implications that can be experimentally tested and controlled.

As a first test of the model, we performed a series of spatial updating experiments in different virtual environments. For example, we selectively disabled either the relative motion branch or absolute location branch by either removing all useful landmarks (Riecke et al., VSS 2002) or by eliminating all motion cues in a "teleport" condition, respectively (Riecke et al., OPAM 2002). In the latter teleport experiment, instantaneous spatial updating was able to compensate for the missing motion information and resulting lack of continuous spatial updating without any significant decrease in performance. This confirmed our distinction between continuous and instantaneous spatial updating as two separate processes that can serve as a mutual backup-system.

• Conclusions

Benefits of the model:

- *Provides a coherent representation*
- *Helps to structure scientific reasoning*
- *Can be used to generate testable predictions*
- *Pinpoints potential causes of spatial orientation problems (in VR in particular)*

This framework is intended as a working hypotheses that can assist in analyzing spatial situations and experimental results. It provides a coherent representation for the large number of experimental paradigms and results and can thus allow for a unifying big picture that might help to structure and clarify our reasoning and discussions. In particular, it proved helpful in understanding the implications if certain processes related to spatial orientation are impaired or defunct (see, e.g., Riecke, 2003, part IV). Furthermore, the human factors issues involved in all Virtual Reality applications can be tackled by analyzing the relevant simulation and display parameters necessary for quick and effortless spatial orientation: Most importantly, any application that does not enable automatic spatial updating should decrease quick and effortless spatial orientation performance and hence unnecessarily increase cognitive load. Only future research, however, will enable us to rigorously test the proposed logical framework and refine or extend it where appropriate.

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