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Qualitative Modeling of Spatial Orientation Processes using Logical Propositions:

Interconnecting Spatial Presence, Spatial Updating, Piloting, and Spatial Cognition

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Abstract. In this paper, we introduce first steps towards a logically consistent framework describing and relating items concerning the phenomena of spatial orientation processes, namely spatial presence, spatial updating, piloting, and spatial cognition. Spatial presence can for this purpose be seen as the consistent feeling of being in a specific spatial context, and intuitively knowing where one is with respect to the immediate surround. The core idea of the framework is to model spatial orientation-related issues by analyzing their logical and functional relations. This is done by determining necessary and/or sufficient conditions between related items like spatial presence, spatial orientation, and spatial updating. This eventually leads to a set of necessary prerequisites and sufficient conditions for those items. More specifically, the logical structure of our framework suggests novel ways of quantifying spatial presence and spatial updating. Furthermore, it allows to disambiguate between two complementing types of automatic spatial updating: On the one hand, the well-known continuous spatial updating induced by continuous movement information. On the other hand, a novel type of discontinuous, teleport-like "instantaneous spatial updating" that allows participants to quickly adopt the reference frame of a new location without any explicit motion cues.

Keywords: spatial presence, spatial updating, human spatial cognition, logic, framework, terminology

1 Introduction

Our main goal is to understand issues and terms related to spatial orientation, spatial updating, and spatial presence by analyzing their logical and functional relations. Here, we present first steps towards a logically consistent framework describing and relating the associated items. This is done by trying to determine a set of necessary prerequisites and sufficient conditions. For example, it is evident that ego-motion perception cannot occur without some kind of motion perception. That is, intact ego-motion perception seems to be logically dependent on intact 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* $\Rightarrow$ *motion perception*" using standard logical notation (see Table 1).

Providing a coherent representation for the large number of experimental paradigms and results can furthermore allow for a unifying "big picture" that might help to structure and clarify our reasoning and discussions. Last but not least, it can suggest novel experiments and experimental paradigms, allow for testable predictions, and stimulate the scientific discussion. That is, the underlying logic of our model suggests novel experimental paradigms that can pinpoint critical factors for good spatial orientation. More specifically, we were able to derive novel paradigms for quantifying spatial presence and spatial updating, and for disambiguating between continuous and instantaneous spatial updating (Riecke, 2003, part III). "Spatial presence" can be understood as the consistent "gut" feeling of being in a specific spatial context, and intuitively and spontaneously knowing where one is with respect to the immediate surround. As we will argue later, spatial presence might be a critical factor for achieving and understanding spatial updating and consequently also for quick and intuitive spatial orientation. Hence, any reliable quantification method that extends beyond the typically used subjective questionnaires might be quite helpful. Furthermore, analyzing experimental results in its context might allow for a deeper understanding of the underlying processes and could help to adapt and refine the framework. In its current state, this framework is being used for understanding and analyzing what is happening in certain spatial orientation situations or experiments (Riecke, 2003, part IV).

The framework and some of the experiments were inspired by the following observation: In most virtual reality (VR) situations involving simulated movements of the observer, people feel lost or disoriented after only a few simulated motions. In comparable real world situations, however, spatial orientation is typically rather robust and effortless. This suggests that some critical prerequisites of good spatial orientation are missing in most VR simulations, even though they might look great and were rather costly. Comparing experiments in real world and VR offers nevertheless the opportunity to test what was missing in a given simulation. Thus, VR can be used as a flexible research tool for investigating spatial orientation processes. By comparing the necessary and/or sufficient conditions for good spatial orientation, our logical framework can assist in analyzing and understanding why spatial orientation fails in certain situations. By focusing on the hereby determined essential spatial cues and display parameters, one should ultimately be able to design convincing ego-motion simulators.

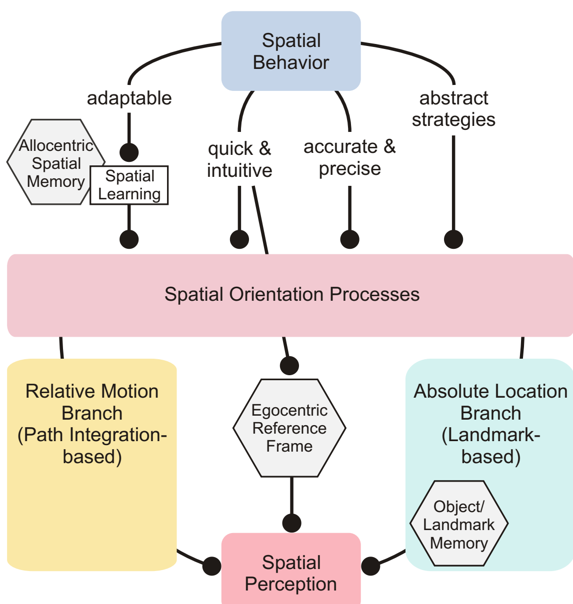


Figure 1: Overview of the model.

Before going into more detail, we would like to first present the overall structure and main components of the framework. The framework in its reduced form is graphically represented in Figure 1. *Spatial behavior*[1] and *spatial perception* are the main components of the action-perception cycle and constitute the top and bottom part of the framework, respectively. Meaningful *spatial behavior* is essentially based and logically dependent on *spatial perception*[2], 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.

The left *relative motion branch* is based on path integration of perceived motions. It is responsible for generating the perception of ego-motion (vection) and the continuous updating of the self-location in space. Being based on path integration, sensory cues stem mainly from vestibular and proprioceptive information and from optic flow. The right *absolute location branch* constitutes an alternative approach to finding ones way around, by using landmarks as reference point. *Object/landmark memory* is hereby involved in the recognition of salient features in the environment.

At the top of the model, we distinguish between four different aspects or properties of *spatial behavior* (**adaptable, quick & intuitive, accurate & precise**, and **abstract strategies**). These different aspects of *spatial behavior* seem to logically depend on different underlying spatial orientation processes and data structures, as will be discussed in detail in section 2. **Adaptable** *spatial behavior* is in addition based on *spatial learning*, which is closely related to *allocentric spatial memory*.

In addition to the left and right branch, we propose a central 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 a process that allows for **quick & intuitive** spatial orientation and prevent us from getting lost, even when we do not constantly pay attention or have other obligations. 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 (see also figure 4).

In the following, the complete framework will first be introduced by describing each item briefly, categorizing it, and stating its hypothesized functional connections. We will continue by discussing some implications for the quantification of spatial updating and spatial presence, and by hypothesizing about further logical connections. That is, this framework will be used to generate hypotheses which can guide future research and can be experimentally tested.

[1]Items of the framework are set in italics for convenience.

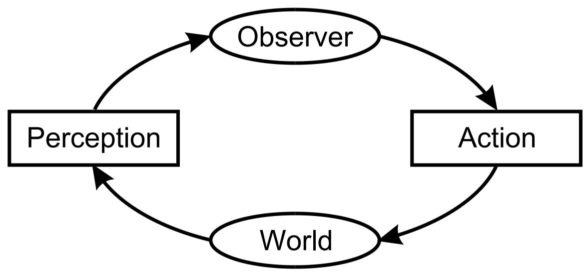
[2]Conversely, *spatial perception* is also influenced on *spatial behavior*, but does not logically require any *spatial behavior*, as is most obvious in the extreme case of locked-in patients.

Name	Statement	Operator	Meaning of statement
simple statements			
assertion	A		A is true
negation	$\neg A$	not	A is false
compound statements and sentential connectives			
disjunction	$A \vee B$	or	either A is true, or B is true, or both
conjunction	$A \wedge B$	and	both A and B are true
implication (conditional)	$A \Rightarrow B$	if ..., then	if A is true, then B is true
equivalence (biconditional)	$A \iff B$	if and only if ..., then	A and B are either both true or both false

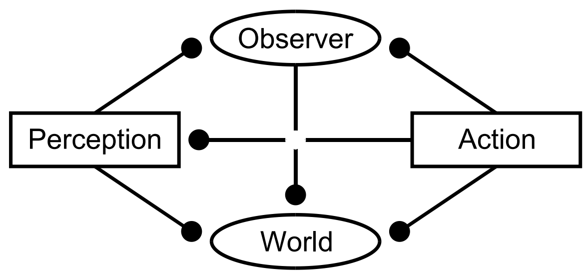
Table 1: Operators and statements as used in propositional logic.

Ideally, the final version of this framework should describe the **logical and functional relationships** between all related terms. As a first step, all terms introduced in this framework are grouped by their coarse classification into GOAL/DESIRED PROPERTY, DATA, or PROCESS. Note that "GOAL/DESIRED PROPERTY" is an attribute of the system described by the framework and not of the framework itself. The logical connections (arrows) between terms are meant to be understood in the mathematical sense, and we use the syntax from propositional logic as summarized in Table 1. Note that if A implies B, this is equivalent to saying that $non - B$ implies $non - A$ ($A \Rightarrow B \iff \neg B \Rightarrow \neg A$). A is therefore a *sufficient* but not a *necessary* prerequisite for B. This is tantamount to saying that B is a *necessary* but *not sufficient* prerequisite for A (contraposition). Please note also that the **information flow** is in most cases in the opposite direction, i.e, from B to A. That is, B is typically "more general" and does include (in the mathematical sense) the more specific A. The difference between logical implications and information flow is illustrated in figure 2, using the simple example of the well-known action-perception loop.

Note that the individual items of the framework are not meant to be understood as simple yes-or-no decisions, such as "either spatial updating works, or else it does not". As human spatial orientation is like most mental processes highly complex and error-tolerant, this would oversimplify things. Rather, we would like to propose a more qualitative interpretation of the logical connections for this framework, much like a fuzzy logic approach. In this manner, $A \Rightarrow B \iff \neg B \Rightarrow \neg A$ would imply that, e.g., "if B is impaired, so is A", or "if A works well, so does B". Furthermore, "if B does not work or exist at all, A is also substantially impaired or defunct".



(a) Information flow representation



(b) Logical connectors representation

Figure 2: Action-perception 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*.

2 Framework

The framework is graphically represented in Figure 3 and will be introduced in detail below. It covers on the vertical axis items ranging from low-level processes like spatial perception at the bottom to high-level processes like spatial behavior at the top. On the horizontal axis, the range spans from reflexive to cognitive control of behavior. This model is built on experimental evidence as well as working hypotheses. That is, we will hypothesize about further connections that are plausible and helpful in interpreting experimental results, but not yet well-grounded on experimental data. These hypothesized connections, however, suggest novel ways of quantifying spatial updating and spatial presence by measuring the adjacent, logically related items of the framework. An exhaustive analysis would unfortunately go beyond the scope of this paper.

In the following two paragraphs, we will introduce three goals or desired system properties that can be seen as a motivation and prerequisite for successful spatial behavior.

2.1 Overall goal guiding this framework: *Spatial Orientation*

All moving organisms have the goal of finding for example food, shelter or ones way through the world without constantly getting lost. All these tasks critically rely on spatial orientation. Hence, our framework has to follow this global aim of spatial orientation as a critical boundary condition for successful spatial behavior. Homing is one prominent example from the literature. The ability to find the way back to the origin of an excursion can be found in most moving species (from ants to humans) (Klatzky, Loomis, & Golledge, 1997; Maurer & Séguinot, 1995; Mittelstaedt & Mittelstaedt, 1982).

2.2 Additional goals guiding this framework: *Consistency* and *Continuity*

Perception is in many respects *continuous* in space and time. Furthermore, the different sensory modalities are typically found to contribute to one *consistent* percept of the world. That is, the relation between oneself and the surrounding real world is spatio-temporally continuous and consistent. Unless we navigate computer-generated worlds, we are neither teleported in space or time (discontinuity) nor do we perceive ourselves to be at several places at the same time (inconsistency). Both *consistency* and *continuity* of the self-to-world relation should therefore be additional desired properties in our framework. Conversely, any kind of inconsistency or discontinuity potentially reduces spatial orientation abilities and should thus be avoided in the design of VR applications. In general, organism might also use this continuity of perception to deduce high spatio-temporal correlations in order to statistically learn properties of the world (Bayesian approach). Hence, it seems plausible to include both *consistency* and *continuity* in the framework. Spatio-temporal continuity is also an important prerequisite when we learn new objects (Wallis & Bülthoff, 2001). This aspect has been successfully implemented in a machine vision recognition system (Bülthoff, Wallraven, & Graf, 2002; Wallraven & Bülthoff, 2001).

Overview In the following, we will try to guide the reader sequentially through this model in a bottom-up manner: We will start with the most fundamental processes and data structures and gradually work our way up until we have all the main ingredients enabling good spatial orientation, which is our overall guiding goal. After briefly describing and categorizing each term, we will state the most relevant logical and/or functional connections to the aforementioned terms. Finally, some extensions and debatable hypotheses are put forward to be discussed in a larger context. Figure 3 shows the complete overview. As the complete model is rather complex, we advise the reader to focus on the terms and relations that have been introduced up to that point. We will start by describing the path integration-based left branch of the framework.

Spatial Perception [PROCESS] Physical stimuli of the surround can be perceived in multiple dimensions and modalities. We group here all kinds of perception, regardless of their sensory modality (e.g., visual, auditory, haptic, kinesthetic etc.) into *spatial perception* if the percept covers some spatial aspect of the stimulus. For the purpose of the overall framework, we do not need or intend to refine this rather coarse and low-level definition of *spatial perception*. Its main purpose is to constitute the basis and necessary prerequisite for the whole framework.

Motion Perception [PROCESS] When we perceive temporal changes of spatial stimuli, we can have the percept of motion. For example, closely listening to a mosquito can tell us whether it moves or not (auditory *motion perception*). Another example is the perception of visual motion from optic flow using simple Reichardt-detectors (Reichardt, 1961). *Motion perception* depends logically on *spatial perception* in the sense that we cannot perceive any motion if we cannot perceive spatial cues: (*motion perception* $\Rightarrow$ *spatial perception)* $\Longleftrightarrow$ ($\neg$ *spatial perception* $\Rightarrow$ $\neg$ *motion perception*). Furthermore, only if continuous changes in space occur over time can we perceive motion. (Under certain conditions, however, small spatial jumps can be perceived (interpreted) as “apparent motion”).

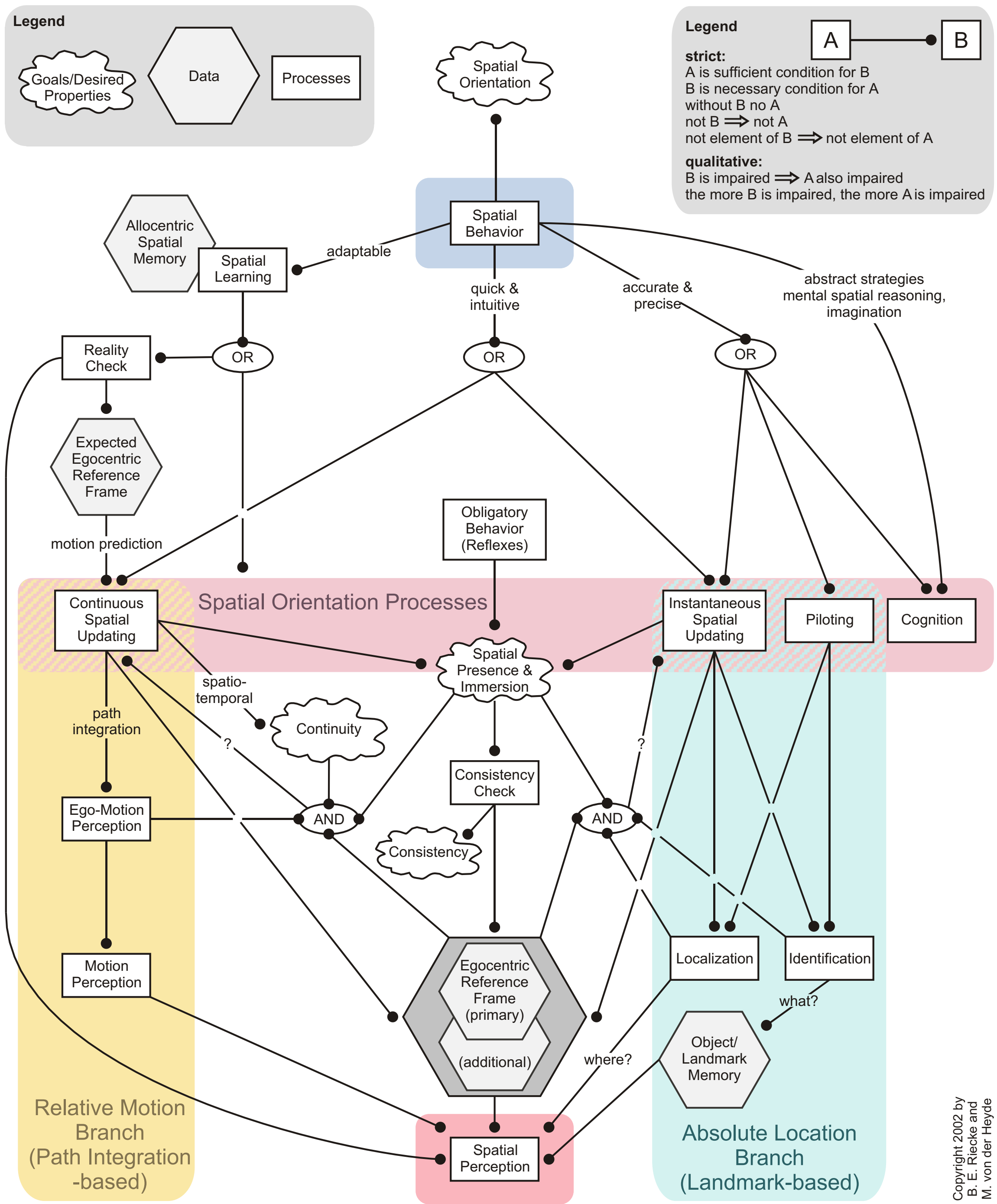


Figure 3: Conceptual framework, as described in the text.

Ego-Motion Perception [Process] If perceived motion is interpreted as self-motion of the observer and not just as a motion of some entity relative to the (stationary) world or observer, we call this phenomenon *ego-motion perception*. Whenever we move through the world, we typically have the percept of ego-motion. The classical example for illusory *ego-motion perception* is visually induced vection (feeling of ego-motion) that can be achieved by presenting a rotating optic flow pattern in an optic drum for several seconds (see, e.g., Dichgans & Brandt, 1978; Fischer & Kornmüller, 1930; Mach, 1922). Obviously, without perceiving any motion in any modality, one would not feel any ego-motion. Therefore, we can state: *ego-motion perception* ⇒ *motion perception*.

Egocentric Reference Frame [DATA] An *egocentric reference frame* can be understood as a mental representation of the "world in our head", as seen from the first-person perspective. This mental model is thought to contain at least the immediate surround or scene. We do not assume any preferred storage format like body schemes or specific coordinate systems. Even if this mental model does not explicitly exist, it makes nevertheless sense to store somewhere the existing knowledge of the immediate surround from the egocentric perspective, as this is the perspective from which we interact with the environment by grasping objects, moving towards them etc.

Incoming information from several modalities can code multiple *egocentric reference frames*. The most prominent or salient one, on which the majority of sensory inputs agree, is called the primary *egocentric reference frame,* which can be in conflict with additional (secondary) reference frames indicated by other sensory input. In most VR applications, for example, at least two competing *egocentric reference frames* are present: On the one hand, the intended or simulated one, that is, the reference frame of the virtual environment. On the other hand, participants are embedded in the physical reference frame of the simulation room. Hence, the *egocentric reference frames* depend critically on *spatial perception*: *egocentric reference frame* ⇒ *spatial perception,* because without (typically multi-modal) perception we would not have the basis for the perceived egocentric perspective. This connection is not further specified here, but is supposed to cover the dependency on multiple modalities.

Consistency [GOAL/DESIRED PROPERTY] As stated in the introduction, we propose the overall goal of a spatio-temporally consistent relation between oneself and the surround.

Consistency Check [PROCESS] In connection to an existing *egocentric reference frame* and the overall goal of *consistency*, we propose the notion of a *consistency check*: At any moment, we should have one and only one consistent mental reference frame that defines our perceived ego-position in the world. That is, both an *egocentric reference frame* and *consistency* are necessary prerequisites for a *consistency check*. Conversely, without the overall goal of *consistency* and the existence of the data structure (*egocentric reference frame*) there would be no process checking for consistency: *Consistency check* ⇒ *egocentric reference frames* and *consistency check* ⇒ *consistency*.

This *consistency check* is related to *spatial presence & immersion*: When directly perceiving the real world, we typically feel spatially present. Total spatial presence can thus be considered the "default". If the perceived stimuli can be consistently embedded in the primary reference frame, everything is fine, and spatial presence (intenseness of being there) will be high. If, on the other hand, the perceived stimuli cannot be consistency embedded into the same primary reference frame, the intensity of the primary reference frame might be reduced and "breaks in presence" (BIP, (Slater, 2002)) can occur. For example, if you are in the midst of a dream and the telephone rings, you will either incorporate the ringing into your dream, or else you will probably wake up. That is, either the primary reference frame (the dream) continues to dominate the secondary reference frame (the physical surround), or a break in presence (and sleep) will occur and and you will wake up. In that moment, the primary and secondary reference frame will be swapped, and the real world will take over. The equivalent can occur in VR simulations: Any events form the physical surround that cannnot be integrated into the virtual world competes with the simulation and will be detected by the *consistency check*, thus disturbing presence.

Spatial Presence & Immersion [GOAL/DESIRED PROPERTY] *Spatial presence* can be regarded as the consistent feeling of being in a specific spatial context, and intuitively knowing where one is with respect to the immediate surround. *Immersion,* on the other hand, could be seen as the subjective feeling of being fully drawn into that spatial context. For the sake of simplicity, however, we do not distinguish between *spatial presence* and *immersion* in this framework and therefore put them into the same box in Figure 3.

Spatial presence & immersion requires the functioning and positive outcome of the *consistency check* of the *egocentric reference frame*: If we do not agree on one single (consistent) reference frame at a time, we cannot be fully immersed in the spatial situation (Regenbrecht, 1999) (*spatial presence & immersion* ⇒ *consistency check*). Furthermore, without the knowledge of some egocentric spatial reference frame, we would obviously not be able to immerse into anything (*spatial presence & immersion* ⇒ *consistency check* ⇒ *egocentric reference frame*).

In virtual reality applications, we can perceive high *spatial presence & immersion* only if the simulated world is consistently accepted as the only reference frame. That is, in order to be fully immersed and spatially present in the simulated world, one has to "forget" about the physical reference frame of the simulator (which would constitute a second, conflicting reference frame) or else the consistency check would detect a conflict.

If one wishes to logically distinguish between *spatial presence* and *immersion*, we would propose to see *immersion* as a logical prerequisite for *spatial presence*, in the sense of *spatial presence* ⇒ *immersion*. That is, no *spatial presence* without *immersion*. This proposition is in agreement with the so-called "book problem" in presence research (e.g., Schubert, 2002): When reading a book, the reader can be drawn into the book and feel immersed without feeling spatially present at the described location (but not the other way around). It appears to us as if immersion might be closely related to the well-studied phenomenon of "flow" states (Csikszentmihalyi, 1991). These are enjoyable states of consciousness where one is so completely focused and concentrated on one activity that it amounts to absolute absorption.

Obligatory Behavior (Reflexes) [PROCESS] For the first time in this paper we would like to introduce something which can actually be measured directly: the process of *obligatory behavior (reflexes)*, which cannot easily be voluntarily suppressed. For example, people with fear of heights cannot help but be afraid if they stand close to an abyss. The same is true for fear of flight or fear of narrow spaces. For example, people with arachnophobia (fear of spiders) might not like to look at pictures of spiders, but that would most certainly not elicit any spatial response like running away. Only if the spider is in a spatial context and crawling towards them would they react spatially by trying to escape. In sum, *obligatory behavior* in this context is meant to refer to compulsory behavior that is elicited by a spatial context or situation. That is, it would seem most natural for us to dodge away if an unknown object flies at high speed towards our head.

One critical point in those situations is to believe the actual danger - that is to feel immersed and spatially present: *Obligatory behavior* ⇒ *spatial presence & immersion*. Without the immersion and spatial presence, the obligatory response is not elicited. This means for example that people with fear of height do not feel that fear if the are not fully immersed into the situation of, e.g., standing at the edge of a cliff (Regenbrecht, 1999). Conversely, if we observe intact reflexive behavior, the participant was spatially present and immersed. That is, *spatial presence & immersion* can be quantified indirectly be measuring obligatory spatial behavior.

It is to be noted, however, that for phobic people, merely *imagining* a fear-inducing situation can elicit all characteristics of a panic attack. Here, we would argue that they feel fully immersed in their *imagined* environment. This suggests that in extreme cases, our framework can operate on purely imagined space, too.

Continuity [GOAL/DESIRED PROPERTY] As mentioned in the introduction, one of the overall desired properties of perception is the apparent *continuity* of the perceived stimulus in particular and the world in general (at least for self-initiated ego-motions). We propose that this property can be seen as the guiding goal of the overall system.

Continuous Spatial Updating [PROCESS] When we move, all spatial relationships between ourselves and the environment change. Nonetheless, we feel immersed in the current surround and naturally experience spatial presence. Apparently, some robust process continuously updates these self-to-world relationships as we move: This *continuous spatial updating* process refers to the incremental transformation of our *egocentric reference frame* based on relative positional and rotational information. That is, it can operate without any landmarks, by incrementally updating the *egocentric reference frame* using perceived velocity, acceleration, and relative displacements. Blindfolded walking with ears muffled is the stereotypical example for this process. See figure 4 for an overview of different spatial updating processes.

More specifically, convincing *ego-motion perception*, *spatial presence & immersion*, *egocentric reference frame* as well as *continuity* are necessary prerequisites for *continuous spatial updating*. Simply put, we cannot update any ego-position if we cannot perceive its changes (*continuous spatial updating* ⇒ *ego-motion perception*). This part is often understood as path integration. Furthermore, we cannot update to a new location in space if we are not already spatially present at any location beforehand and possess a corresponding *egocentric reference frame* - otherwise there would be nothing to update (*continuous spatial updating* ⇒ *spatial presence & immersion* and *continuous spatial updating* ⇒ *egocentric reference frame*). Finally, a continuous update is only possible if the sequential changes are continuous in time and space (*continuous spatial updating* ⇒ *continuity*). Without *continuous spatial updating*, the *egocentric spatial reference* frame would become increasingly misaligned, which would eventually lead to a discontinuity the next time *instantaneous spatial updating* realigned the *egocentric reference frame* (see below).

Expected Egocentric Reference Frame [DATA] Executing all possible behaviors in order to test their potential outcome is very inefficient. A more efficient approach would be to automatically predict and imagine what we would perceive if we would perform a certain movement. In this manner, we generate an expectation of what we should perceive if we had actually performed that motion. Moving in space is in this

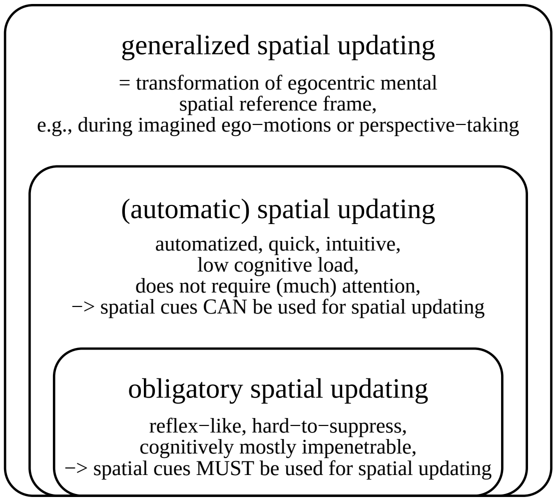


Figure 4: Connection between generalized, automatic, and obligatory spatial updating. At the most general level, **generalized spatial updating** refers to all transformations of our egocentric mental spatial reference frame. This includes mental perspective-taking or consciously updating our egocentric reference frame during imagined ego-motions. **Automatic spatial updating**, which is often referred to as simply spatial updating, is a more specific subset and refers to the largely automated transformations of our mental egocentric reference frame. Due to this automaticity, both the cognitive load and attentional demands are minimal, if not zero. **Obligatory spatial updating** is a subset of the more general (automatic) spatial updating. It refers to the reflex-like, hard-to-suppress and thus cognitively almost impenetrable phenomenon of perceived spatial cues triggering spatial updating, whether we want to or not. Conversely, spatial cues are called sufficient for triggering obligatory spatial updating if they *must* be used, i.e., if they mandatorily transform our mental spatial reference frame whether we want to or not. Furthermore, spatial cues are called sufficient for enabling (automatic) spatial updating if they *can* trigger this automatic process, but do not necessarily *have* to be used.

sense very predictable by the organism and therefore we hypothesize: *expected egocentric reference frame* ⇒ *continuous spatial updating* in the sense that without *continuous spatial updating* one would not be able to predict the changed percept of the world.

Reality Check [PROCESS] Once we have an expectation of what we ought to perceive for a given motion, we can compare the actual percept to the predicted one. That is, we need both an *expected egocentric reference frame* and *spatial perception* to allow for the *reality check* (*reality check* ⇒ *expected egocentric reference frame* and *reality check* ⇒ *spatial perception*). If they match, everything is fine, and the reality check process will probably not come to consciousness or require any attention. If not, this might require some attention or action, that is, we might for example want to look again to make sure that everything is okay or allocate some cognitive resources to resolve the mismatch or act appropriately. An example might illustrate this.

If we walk on ice and slip, the outcome of our behavior and motion (slipping) does not longer match the expectation (walking). The *reality check* detects this discrepancy and brings it to consciousness and alerts us. This is necessary to respond appropriately and prevent one from falling.

This double-checking is the obvious connection to *spatial perception*. One rather far-fetched hypothesis would be to propose: *spatial perception* ⇒ *reality check*, implying that we can only perceive *if* we expect and maybe even *what* we expect. Naturally, this cannot be sufficient to explain perception, but it sheds a new light on change blindness results - even considerable changes in our surround go unnoticed if we do not expect them to occur (Simons & Levin, 1997).

Spatial Learning [PROCESS] If the *reality check* encounters an unexpected event, there might be something we could learn from this discrepancy. Since the organism cannot predict everything right from the start, its internal prediction model needs to be developed though learning. Many learning algorithms as understood in the neurosciences require an error signal, which can be defined as the difference between stimulus and prediction.

As we are concerned here with *spatial* behavior only, we would like to constrain ourselves here to *spatial learning*. *Spatial learning* can be seen as the process of building up and modifying spatial knowledge, that is, the process which operates over time on the *allocentric spatial memory* (see below). We hypothesize that spatial learning requires either a *reality check* or at least one of the four spatial orientation processes (*spatial learning* ⇒ (*reality check* ∨ *any spatial orientation process*)).

Four examples might illustrate this. Homing experiments without landmarks (Loomis et al., 1999; Klatzky et al., 1997) are the stereotypical example for learning how to find home based on relative motion information and *continuous spatial updating* only (left branch). There are no real world examples where only *instantaneous spatial updating* is used for spatial learning. Rapid serial presentation of images of an unknown scene might be a way to test if *instantaneous spatial updating* can nevertheless be used for spatial learning. When driving around unknown environments, landmark based large-scale navigation (*piloting*) is probably the predominant spatial orientation process that helps us to learn the new environment. An example involving higher cognitive spatial orientation processes is learning an environment from abstract knowledge like maps.

Allocentric Spatial Memory [DATA] Through *spatial learning*, we can acquire *allocentric spatial memory*, e.g., spatial memory in the form of a "cognitive map" allowing for novel shortcuts (see, e.g. Poucet, 1993; Tolman, 1948; Trullier, Wiener, Berthoz, & Meyer, 1997). Therefore, *spatial learning* can be seen as an ongoing process operating on the knowledge stored in *allocentric spatial memory*. We would like to state that learning and memory are tightly coupled, require one another and thus cannot be strictly separated. We express this as a direct coupling (equivalence on the logical, but of course not on a functional level) between *spatial learning* and *allocentric spatial memory*.

Object/Landmark Memory [DATA] Having described the path integration-based left branch of the framework, we will now discuss the more static, absolute location-based branch. *Object/landmark memory*, which is the most basic data structure in our framework, contains knowledge about objects and landmarks *without* their spatial context or relationships. This is the data structure needed for, e.g., object recognition (see below). We do not assume any preferred storage format, but presume that we cannot built up any knowledge of spatially extended objects or landmarks without some kind of *spatial perception* (*object and landmark memory* $\Rightarrow$ *spatial perception*).

Identification [PROCESS] Having the ability to store knowledge about objects and landmarks, it makes sense to demand some recognition process which can identify objects, in order to label them as individuals and potentially recognized them later. This *identification* process can be seen as the "what path" in the perception model by Mishkin, Ungerleider, and Macko (1983). The logical relation here is as follows: *identification* $\Rightarrow$ *object and landmark memory*. In other words, if one cannot remember any objects, it should not be possible to recognize and to identify them later.

Localization [PROCESS] As soon as we perceive anything spatially, we can localize it even without necessarily being able to identify it. That is, the *localization* process does not assume any attribution of identity. One could compare this to the "where path" in the Mishkin et al. (1983) model of perception. The logical relation between these two terms is: *localization* $\Rightarrow$ *spatial perception*. In other words, without any *spatial perception* we could have no *localization* process (i.e., $\neg$ *spatial perception* $\Rightarrow$ $\neg$ *localization*).

Instantaneous Spatial Updating [PROCESS] In order to convincingly explain recent results from spatial updating experiments by Riecke, von der Heyde, and Bülthoff (2002a) in the context of this framework, we need to refine our concept of spatial updating. Apart form the well-known smooth spatial updating induced by continuous movement information, Riecke et al. (2002a) found also a discontinuous, teleport-like "instantaneous spatial updating" that allowed participants to quickly adopt a new orientation without any explicit motion cues. These slide-show type presentations of new orientations were even sufficient in triggering obligatory, reflex-like spatial updating. This made it necessary to extend the prevailing definition of spatial updating and distinguish between the classical *continuous spatial updating* known from the blindfolded spatial updating literature and the hereby introduced "*instantaneous spatial updating*".

Spatial updating in general can be thought of as the spatial transformation process operating on the egocentric mental spatial representation (see figure 4). In this manner, *continuous spatial updating* is the process of continuously and incrementally (smoothly) transforming our egocentric reference frame, where as *instantaneous spatial updating* is the immediate, and if need be discontinuous ("jump" - or "teleport"-like) process. Where as the continuous process might have some limitations in terms of transformation speed (e.g., a limited mental rotation speed), the instantaneous one probably does not.

As *continuous spatial updating* alone is based on path integration and leads to exponentially increasing alignment errors over time, it seems sensible to propose a second process that can re-anchor the potentially misaligned mental reference frame to the physical surround. We would like to introduce the term *instantaneous spatial updating* to refer to this process. To give an example, imagine the following: You are at home at night when the main fuse blows. You will have to walk around in darkness until you manage to find the fuse box or some light source. When walking around in complete darkness, you become increasingly uncertain about our current ego-position. That is, you still have some intuitive feeling of where you are, but you would not bet much on the exact location. The situation changes as soon as you can perceive the location of known landmarks. This instantaneous position fixing could occur via different sensory modalities: Auditorily, for example the phone could be ringing. Haptically, you might touch or run into the kitchen table. Visually, somebody else might already have replaced the fuse, or lightning might have lit the room for a fraction of a second. That is, any clearly identifiable spatial cue (landmark) could re-anchor our mental reference frame instantaneously, without much cognitive effort or time needed. This process of automatically re-aligning or re-anchoring the mental reference frame to the surround is what we refer to as *instantaneous spatial updating*.

When locomoting under full-cue conditions, this instantaneous spatial updating probably occurs automatically at any instance in time and is thus indistinguishable from continuous spatial updating, as both processes are in close agreement and complement each other. Moreover, they can be considered as a mutual back-up system for the case that one of them fails or does not receive sufficient information.

Our distinction between continuous and instantaneous spatial updating bears some resemblance to Kosslyn's distinction between "shift transformations" and "blink transformations", respectively (Kosslyn, 1994). Shift transformations are responsible for smooth and seemingly continuous transformations of mental images like object translations and rotations. If, however, "an image object must be transformed a large amount, the image may be allowed to fade and a new one is generated" (Kosslyn, 1994, p. 402), which Kosslyn refers to as "blink transformation". Note that shift and blink transformations refer to mental object image transformations that are continuous and discontinuous, respectively. Continuous and instantaneous spatial updating, on the other hand, refer to the transformation of the complete mental egocentric spatial reference frame, which involves a change in the observer's position or orientation. Furthermore, spatial updating is normally automated and reflex-like (obligatory), where as Kosslyn's image transformations are typically deliberate, cognitive processes (i.e., neither automatic nor obligatory). These fundamental differences might explain the often found advantage of self motions over object motions for the updating of physical as well as imagined rotations (Simons & Wang, 1998; Wang & Simons, 1999; Simons, Wang, & Roddenberry, 2002; Wraga, Creem, & Proffitt, 2000, 2003).

In sum, *instantaneous spatial updating* refers to the reflex-like process of re-aligning or re-anchoring the mental spatial reference frame to the surround using position-fixing via landmarks (*instantaneous spatial updating* ⇒ *egocentric reference frame*). This process can be triggered by, for example, haptic, auditory, and, probably most frequently, visual landmarks. *Instantaneous spatial updating* is thus critically depending both on the *localization* and *identification* process: *Instantaneous spatial updating* ⇒ *localization* process means that it would not make sense to re-anchor the mental reference frame if we were not sure about the exact coordinates to use. Moreover, *instantaneous spatial updating* ⇒ *identification* means that it would not make sense to re-anchor the mental reference frame if we could not recognize anything familiar that told us where we were. Furthermore, we propose that *spatial presence & immersion* is a necessary prerequisite for automatically triggering *instantaneous spatial updating*, just as it was for *continuous spatial updating* (*instantaneous spatial updating* ⇒ *spatial presence & immersion*).

Piloting [PROCESS] Position- or recognition-based navigation (also called *piloting*) uses exteroceptive information to determine ones current position and orientation. Such information sources include visible, audible or otherwise localizable and identifiable reference points, so-called landmarks (i.e., distinct, stationary, and salient objects or cues). This implies *piloting* ⇒ *localization* and *piloting* ⇒ *identification*. Many studies have demonstrated the usage and usability of different types of landmarks for navigation purposes, (see Golledge (1999), Hunt and Waller (1999) for an extensive review). Piloting allows for correction of errors in perceived position and orientation through reference points (position fixing) and is thus well-suited for large-scale navigation. Piloting mechanisms often used include scene matching or recognition-triggered responses. Compared to *instantaneous spatial updating*, *piloting* is neither reflex-like nor automated, and does not require any aligned egocentric reference frame. Note that no higher cognitive processes are needed for piloting, as even simple robots can use for example snapshot-based piloting for navigation (Franz, Schölkopf, Mallot, & Bülthoff, 1998).

Spatial Orientation [GOAL/DESIRED PROPERTY] The main overall goal of the system described by the framework is in this context, as stated above, proper *spatial orientation*, which is essentially the ability (not the behavior itself) to easily find ones way around.

Spatial Behavior [PROCESS] Last but not least, we seem to have all basic ingredients to define *spatial behavior* as behavior performed in space and time and at the same time relying on spatial knowledge about the world.

First of all, it seems plausible to assume *spatial behavior* ⇒ *spatial learning*: Without learning spatial knowledge, we would not be able to adapt to new situations and find our way around in a novel or changing environment. That is, we propose that *spatial learning* is required for the **adaptability** of *spatial behavior*.

As spatial behavior (especially in animals) is typically quick and intuitive, many of the required computational processes need to be largely automated. Hence, we propose that automatic spatial updating is a necessary prerequisite for **quick & intuitive** *spatial behavior*. Therefore, we propose that quick and intuitive *spatial behavior* ⇒ *continuous spatial updating* and/or *spatial behavior* ⇒ *instantaneous spatial up-*

dating. Consequently, quick and intuitive *spatial behavior* should not be possible without either *continuous spatial updating* or *instantaneous spatial updating* or both being operational. As both continuous and instantaneous spatial updating logically imply *spatial presence & immersion*, we hereby indirectly claim that *spatial behavior* ⇒ *spatial presence & immersion*. In other words, when we do not feel ourselves at a specific location and orientation, we cannot interact with the world in a natural and effortless manner. Hence, we proposed indirectly that *spatial presence & immersion* are required for quick and intuitive *spatial behavior*.

For the consistency of this model, we would like to exclude for the time being behavior that can be modeled by simple direct coupling of perception and action, without any spatial knowledge (e.g., Braitenberg vehicles (Braitenberg, 1984)). Instead, we do limit our view of *spatial behavior* as such being motivated by and thus depending on good *spatial orientation*. Without *spatial orientation* we are not able to perform the required *spatial behavior* (*spatial behavior* ⇒ *spatial orientation*). Consequently, *spatial behavior* can be used to measure and evaluate the successful *spatial orientation* in psychological experiments.

Obviously enough, spatial behavior should be most accurate and precise if we can recognize and localize unique reference points. As *instantaneous spatial updating* as well as *piloting* are the two processes relying on the *localization* and *identification* of such landmarks, we propose that at least one of them has to work for us to have accurate and precise spatial behavior. Hence, we propose that **accurate & precise** *spatial behavior* ⇒ *instantaneous spatial updating* or *spatial behavior* ⇒ *piloting*.

Having identified specific items that are required for different aspects of *spatial behavior* (accurate & precise, adaptable, and quick & intuitive spatial behavior), we are enabled to analyze spatial or experimental situations accordingly: If the observed spatial behavior is for example accurate and precise, but response times are long and participants report not having much of an intuitive spatial orientation, we could conclude that *piloting* (the landmark-based static right branch of the framework) is intact, whereas *continuous spatial updating* as well as *instantaneous spatial updating* are probably largely impaired. This might in turn, for example, be due to the lack of convincing *spatial presence & immersion.*

Conversely, if the observed spatial behavior is quick & intuitive but lacks accuracy and precision, we would argue that automatic *continuous spatial updating* was working, but neither *instantaneous spatial updating* nor *piloting* were intact. Thus, the central and left relative motion-based part seem to be intact, where as the absolute location-based right branch is not. Examples for this case include blindfolded walking, getting lost in deep forest, and of course visually induced vection in an optic drum. Note that sensory cues that might allow for *continuous spatial updating* include vestibular cues (accelerations), proprioceptive cues (e.g., from walking), but also visual or auditory from optic or acoustic flow, respectively.

2.3 Where does cognition fit into the model?

So far we have attempted to lay out a consistent framework based on logical connections between related items. The contribution of higher cognitive processes or strategies has so far not been taken into consideration. Moreover, especially the lower part of the framework seems to be largely beyond conscious control: For example, even if we might consciously decide to do so, it is virtually impossible to influence *identification* (not recognize your friend's face) or *ego-motion perception* (consciously elicit the convincing sensation of ego-motion unless being intoxicated).

So where does cognition fit into this model? By its very nature, cognition is flexible and versatile and consequently cannot simply be represented as one box logically dependent on other boxes. Rather, cognition might be considered as an optional process that can be resorted to if the partly automated framework fails or does not allow for the desired spatial behavior. That is, we have conscious access to for example the lower items of the framework (*motion perception*, *localization*, and *identification*), even though we cannot consciously control them. Hence, we can for example consciously question *motion perception* to cognitively derive the simulated displacement, even though we might not perceive any *ego-motion*. We are, however, unable to use this abstract knowledge about the simulated turning angle to intentionally evoke the percept of convincing ego-motion. That is, the lower items in the framework can be queried, but are nevertheless to a large degree cognitively impenetrable.

Cognition [PROCESS] Ultimately, this leads to a fourth connection to *spatial behavior*: Higher cognitive processes (*cognition*) can be used to develop for example novel strategies to solve a complex navigation problem, or to use mental spatial reasoning or spatial imagination to derive the desired spatial behavior. For example, finding the shortest route in a subway system might require rather advanced cognitive processing.

Cognition can consequently be considered a necessary condition for *spatial behavior* based on non-automated **abstract strategies**, **mental spatial reasoning**, and **imagination**. This can be represented in the framework as *spatial behavior* ⇒ *cognition*. Due to the inherent flexibility of *cognition*, however, there are no other fixed links to *cognition*. Rather, cognition can be used to flexibly query the desired information from most or maybe even all of the other items of the framework. Hence, if we observe spatial behavior that is neither quick & intuitive nor very accurate & precise, we could argue that the behavior might have been based on abstract cognitive strategies. As mental geometric reasoning can lead to quite accurate and precise spatial behavior, we propose *cognition* as a third possibility for achieving accurate and precise *spatial behavior* (apart from *instantaneous spatial updating* and *piloting*): **Accurate & precise** *spatial behavior* $\Rightarrow$ *cognition*.

2.4 Ways to measure spatial presence and immersion

Until very recently, quantifying presence and immersion has been typically attempted using highly subjective and introspective methods like questionnaires (Hendrix & Barfield, 1996a, 1996b; Ijsselsteijn, Ridder, Freeman, Avons, & Bouwhuis, 2001; Lessiter, Freeman, Keogh, & Davidoff, 2001; Schloerb, 1995; Schubert, Friedmann, & Regenbrecht, 2001; Witmer & Singer, 1998). These methods were an important first step towards understanding the nature and relevance of presence and immersion for many applications, but share certain undesired side-effects. All introspective measures have to somehow explicitly question the participant, which in itself can reduce presence and immersion. Questionnaires in particular do not allow for online measures in the spatial context, as they are used after the exposure. In the following, we would like to sketch novel quantification methods that rely not on introspection but rather on psychophysical measures. They complement the existing methodologies and might allow for more sensitive and reliable online measures even without the participant noticing the measurement. How those results relate to subjective measures still remains an open question.

Having embedded *spatial presence & immersion* into a logical framework allows us to devise new quantification methods by either measuring all necessary prerequisites or, even more elegantly, measuring at least one sufficient condition. As we have seen in the previous section, spatial presence is embedded into a collection of processes with useful and testable properties. We found three sufficient but not necessary prerequisites of spatial presence: *continuous spatial updating, instantaneous spatial updating*, and *obligatory behavior*. In addition, we have one necessary, but not sufficient, prerequisite (*consistency check*). Having laid out the logical framework, we can now use this prerequisite to measure presence: The degree of mismatch between the primary egocentric reference frame and other potentially conflicting reference frames becomes a proposed measure for spatial presence. The actual measurands are the reference frames from different modalities and the potential mismatch between them by appropriate psychophysical methods.

Furthermore, certain spatial behaviors seem impossible without sufficient *spatial presence & immersion*. Measuring the functioning of *obligatory behavior* is a potential and currently discussed method to quantify *spatial presence & immersion*. In the same line of reasoning, effortless *continuous* or *instantaneous spatial updating* cannot occur without sufficient *spatial presence & immersion*. Following the logical chain further up in our model, we see that spatial updating (continuous or instantaneous) is a necessary prerequisite for quick and intuitive *spatial behavior*. Conversely, the observation of such quick and intuitive *spatial behavior* implies automatic spatial updating and consequently also *spatial presence & immersion*. Those examples represent indirect measures of spatial presence that can readily lead to novel experiments complementing current presence research. Riecke, von der Heyde, and Bülthoff (2001) for example developed a rapid pointing paradigm that does not allow participants enough time to use *piloting* or *cognition*. In that manner, possible spatial orientation processes could be reduced to *spatial updating*. As a functioning of at least one of the two *spatial updating* processes implies *spatial presence & immersion*, the results indirectly reflect the degree of *spatial presence & immersion*.

2.5 Further hypotheses about logical relations

So far we tried to sketch a clear chain of logical connections which can be summarized as *spatial behavior* $\Rightarrow$ *spatial perception*, which is plausible per se (see figure 2). In addition to some assumptions we had to make in laying out our string of arguments, we would now like to introduce two hypothetical additional loops. We propose that *spatial presence & immersion, continuity, ego-motion perception* and an *egocentric reference frame* **together** are sufficient to enable proper *continuous spatial updating* (*spatial presence & immersion* $\wedge$ *continuity* $\wedge$ *ego-motion perception* $\wedge$ *egocentric reference frame* $\Rightarrow$ *continuous spatial updating*). In other words, continuous spatial updating should work if all four prerequisites are true. Conversely, if we observe impaired *continuous spatial updating*, then we can conclude that at least one of the prerequisites is violated. ($A \wedge B \wedge C \wedge D \Rightarrow E$ is equivalent to $\neg E \Rightarrow \neg A \vee \neg B \vee \neg C \vee \neg D$).

Taken together with the previously established logical connections (*continuous spatial updating* $\Rightarrow$ *spatial presence & immersion* $\Rightarrow$ *consistency check* $\Rightarrow$ *egocentric reference frame)* $\wedge$ *(continuous spatial up-*

dating $\Rightarrow$ *continuity* $\Rightarrow$ *egocentric reference frame)* $\wedge$ *(continuous spatial updating* $\Rightarrow$ *ego-motion perception*), we can furthermore conclude the following: if any of the four prerequisites is violated, *continuous spatial updating* would be rendered impossible or at least largely impaired ($\neg A \vee \neg B \vee \neg C \vee \neg D \Rightarrow \neg E$). Together with the above argument, this leads to the following equivalence: $\neg E \iff \neg A \vee \neg B \vee \neg C \vee \neg D$, which is the same as saying that $E \iff A \wedge B \wedge C \wedge D$. In other words, this means that instead of measuring *continuous spatial updating*, we can measure *consistency check* $\wedge$ *spatial presence & immersion* $\wedge$ *egocentric reference frame* $\wedge$ *ego-motion perception*.

Furthermore, as *spatial presence & immersion* implies both *consistency check* and *egocentric reference frame*, we can as well state that measuring *continuous spatial updating* is equal to measuring *spatial presence & immersion* $\wedge$ *ego-motion perception*. This opens up many interesting experimental investigations. For example, *spatial presence & immersion* can be quantified by measuring *continuous spatial updating* and *ego-motion perception* and vice versa.

A very similar second loop is located in the absolute location-based right part of the framework. Recent experiments by Riecke, von der Heyde, and Bülthoff (2002b) showed that merely presenting an image of a new orientation in a "teleport" condition without any motion information whatsoever can be sufficient to trigger obligatory spatial updating. Therefore, we propose that *spatial presence & immersion* $\wedge$ *egocentric reference frame* $\wedge$ *localization* $\wedge$ *identification* $\Rightarrow$ *instantaneous spatial updating*. Following the same reasoning as before, this opens up the possibility to measure *instantaneous spatial updating* instead of *spatial presence & immersion* $\wedge$ *localization* $\wedge$ *identification*. Even more pragmatically, one could use standard psychophysics to measure the latter two of the conditions (*localization* $\wedge$ *identification*) as well as the new method of quantifying *instantaneous spatial updating* Riecke et al. (2002b) in order to quantify *spatial presence & immersion* in quasi-static situations.

3 Discussion

So far, we have not attempted to relate each item in the framework to the corresponding functional relations and information flow. Many of the proposed connections may indeed be closely linked to corresponding processing steps and neural connections in the human brain. Most of the boxes might also be considered as being localized in specific brain regions. There is for example a large body of literature arguing that the hippocampus is critically involved in path integration as well as landmark-based navigation and cognitive maps in animals including humans (Berthoz, 1997; Maguire, Frith, Burgess, Donnett, & O'Keefe, 1998; Maguire et al., 1998; McNaughton et al., 1996; Mittelstaedt, 2000; O'Keefe & Dostrovsky, 1971; O'Keefe & Nadel, 1978; Poucet, 1993; Samsonovich & McNaughton, 1997). Furthermore, ego-motion perception seems to be closely linked to the intraparietal sulcus (IPS) in humans and the equivalent area (ventral intraparietal area (VIP)) in macaque monkeys (Bremmer, Klam, Duhamel, Ben Hamed, & Graf, 2002; Bremmer et al., 2001). Trying to associate all the individual boxes and logical connections of the current framework with corresponding neural substrate would be a challenging as well as promising endeavor. Obviously enough, however, it goes well beyond the scope of this paper.

To sum up, can we measure spatial presence now? As Wijnand Ijselstein, one of the leading researchers in the presence community phrased it: "Presence needs to be unambiguously operationalised, and subdivided into its basic components in order for it to be measurable in a way that will make sense." (IJsselsteijn, 2002). In our paper, we attempted this by embedding spatial presence into a logical framework. This allowed us to operationalise spatial presence through a set of necessary and/or sufficient conditions for spatial presence. Instead of subdividing spatial presence itself into its basic components, however, we analyzed related processes. This allowed us to generate a multitude of testable predictions and measurement paradigms for spatial presence itself as well as for related issues like continuous and instantaneous spatial updating.

We are aware that many factors can potentially affect spatial presence. Examples include the (actual or assumed) ability to explore the virtual surround, to interact with it, and to predict the outcome of ones actions (Regenbrecht, 1999; Regenbrecht & Schubert, 2002; Schubert et al., 2001). Narrative components and dramatic effects are further factors that have been shown to enhance spatial presence (Regenbrecht, 1999). None of these factors alone, however, seems to be absolutely required in the sense of spatial presence logically implicating that factor (e.g., *spatial presence* $\not\Rightarrow$ *dramatic effects*). This the reason why those and many other potentially influential factors are missing in our framework. The same is of course true for the other items of the framework.

We hope that the proposed framework will stimulate the scientific discussion and help to clarify our reasoning and discussions, especially when such loosely defined terms as spatial presence, immersion, or spatial updating are involved. Only future research, however, will enable us to rigorously test the proposed logical framework and refine or extend it where appropriate.

In summary, we embedded current terminology from the field of spatial orientation in a functional and logical framework. This framework covers aspects ranging from spatial perception over allocentric and egocentric spatial memory up to spatial behavior. Finally, we used this framework to generate hypotheses which can guide future research and can be experimentally tested.

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