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A Quantitative Measure of Telepresence

Abstract

This paper presents the foundation for a theory of presence that seeks to answer important questions about telepresence and virtual presence. The theory, which develops the definition of telepresence to include virtual presence as a special case, permits the precise definition of various types and degrees of telepresence. General categories of telepresence are defined, using different types of presence that are proposed in the paper. Three types of specifications are used to make the definitions more precise: (1) a set of tasks, (2) a transformation imposed on the human operator's control output and sensory input, and (3) a transformation of the region of presence. The proposed quantitative measure of telepresence involves both objective and subjective measures. The degree of (objective) telepresence is equal to the probability of successfully completing a specified task. The degree of *subjective* telepresence is equal to the probability that a human operator perceives that he or she is physically present in a given remote environment. The measure of subjective telepresence involves a psychophysical test and is analyzed using signal detection theory. Real-world complications are addressed and a practical example of a subjective telepresence test is described.

1 Introduction

Telepresence[1] is a popular idea that is not well defined. In essence the idea is that a person is *in some sense* present in an environment that is physically remote from the person in space. Existing definitions of telepresence and the related concept, virtual presence, depend on the idea that the person *feels* present in the given environment.[2] Unfortunately the latter is not adequate for quantitative investigations (Held & Durlach, 1989, 1992).

This paper seeks to address the problem by defining telepresence in quantitative terms. The discussion also applies to virtual presence, which is shown to be a special case of telepresence. Indeed, the foundation for a theory of presence is developed that permits the precise definition of many different types and de-

1. The term was first introduced in a 1980 *Omni* magazine article written by Minsky (1980), who gave credit to his friend Pat Gunkel for coining the term. The idea is evident earlier, however, in the work of Raymond Goertz in the late 1940s (Johnsen & Corliss, 1971, pp. 120–121; Vertut & Coiffet, 1986, pp. 25–27).

2. For example, Sheridan (1992a, p. 274) defines telepresence "to mean that the human operator receives sufficient information about the teleoperator and the task environment, displayed in a sufficiently natural way, that the operator feels physically present at the remote site." Note that virtual presence is simply the case where the teleoperator and the remote environment are simulated inside a computer.

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grees of presence. At the heart of the theory is the idea that *presence* involves objective interaction.[3]

1.1 Overview of the Theory

A person is *objectively present* in a *remote environment* where the person is *not* physically present, if there is some type of causal interaction between the person and the environment. For example, the person might cause or detect some remote event using a teleoperation system. Clearly, a person can also be objectively present in his or her *local environment* (where the person *is* physically present). It should also be clear to the reader that objective presence, without further specification, implies nothing about how the person *feels*.

The *degree* of objective presence may be defined based on the probability that a given task is completed successfully. For example, a baseball player's batting average is his or her degree of objective presence *in the task* of getting a hit. Similarly, one could define a degree of objective presence based on the probability that a person will perceive a particular word when presented with a given auditory stimulus (Kryter, 1972, p. 174).

Different *types* of objective presence may be defined based on what task is specified and I submit that this is the key to defining telepresence. An important question that is *not* addressed in the paper, however, is how the set of all possible tasks might be partitioned into important types of objective presence. The one case that is discussed in some detail is related to a person's *feeling of presence*.

1.1.1 Subjective Presence. An important category of objective presence is the case where the specified task is for a person to perceive that he or she is physically present in a given environment. For example, if you stop and think about it you will (no doubt) perceive that you are physically present in some environment (wherever you happen to be right now).[4] This is *subjective presence*.

The *degree* of subjective presence is defined to be the probability that a person perceives that he or she is physically present in the given environment. Measuring the degree of subjective presence involves a psychophysical test. For example, one might use a procedure similar to the method of constant stimuli (Gescheider, 1985, pp. 38–39).

Figure 1 illustrates a simple example of such an experiment. In this hypothetical experiment there is a room with a door. The test subject would stand at various locations on a line running through the door and respond to the yes–no question, "are you in the room?" Far to one side of the door the subject would (always) respond, "yes" and far to the other side he or she would (always) say "no." In between the two extremes, the degree of subjective presence is equal to the relative frequency of "yes" responses. For example, I predict that the person would respond "yes" half of the time somewhere in the vicinity of the door; corresponding to a degree of subjective presence equal to ½.

1.1.2 Subjective Telepresence. Existing definitions of telepresence can be made more precise simply using the idea of *subjective presence* rather than vague notions about how a person *feels*.

I propose a strict test of subjective telepresence. In the test a person is asked to decide between two cases presented at random: (1) where the person is physically present in an environment, or (2) where he or she is interacting with the environment via a teleoperation system (see Section 2.1). If the person cannot detect the difference between the two cases then he or she is subjectively telepresent in the given environment. The degree of subjective telepresence is equal to the probability that the person says that he or she is physically present when the person is in fact using the teleoperation system.

3. This aspect of telepresence is often neglected, perhaps because it is so obvious. Nevertheless, telepresence is commonly described in terms of teleoperation, which *implies* an objective interaction between the human operator and the remote environment. The definition proposed by Akin, Minsky, Thiel, and Kurtzman (1983) recognizes objective performance explicitly. They state, "At the worksite, the manipulators have dexterity to allow the operator to perform normal human functions." Unfortunately, this definition neglects some important cases (Held & Durlach, 1989, pp. 28-2 to 28-3; 1992, p. 109) and it is not quantitative.

4. I will sometimes use the less formal pronoun "you" in discussions related to subjective presence because it is something that each of us can experience directly.

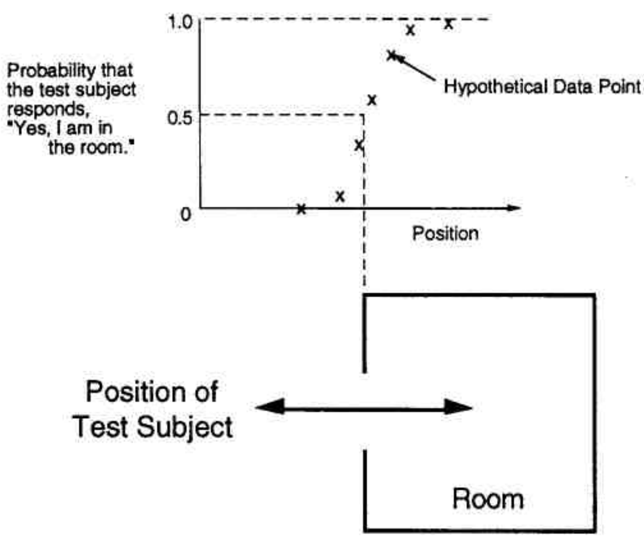

Figure 1. *Hypothetical subjective presence experiment.*

1.1.3 Transformations. Unfortunately, there are two significant problems that must be addressed in order to use the test. First, the test is too strict: no existing teleoperation system is likely to pass it! Second, the test does not apply to environments where it is not possible for a person to be physically present. Solutions to these problems involve two general transformations that further refine the definition of telepresence.

The first type of transformation is a *control/sensory transformation* imposed on the person's interaction with the remote environment. The teleoperation system itself imposes (and may be described by) such a transformation. Additional transformations can be imposed in a subjective telepresence test. The most important general type of additional transformation appears to be a restriction of the flow of information between the person and the teleoperation system. By restricting the interaction between the person and the system the person's detection task in the test is made more difficult. Indeed, in the limit where there is no interaction, there is no way for a person to detect a difference between the two cases of the test. As a result, an additional set of control/sensory transformations can always be found that will make it possible for any teleoperation system to pass the test.

The conditions of the test, including the additional control/sensory transformation that is imposed, define the type of subjective telepresence that is observed. Assuming that it is *not* just the trivial type (i.e., no interaction), one can study how variations in parameters of the system and other factors affect the degree of subjective telepresence.

The second type of transformation is a *transformation of the region of presence.* The general idea is that a person can perceive himself or herself to be in one environment while physically interacting with a different environment. The transformation is a mapping between the two environments.

This type of transformation is simply a way of defining subjective telepresence in environments where it is not possible for a person to be physically present. For example, *virtual presence* may be defined as subjective telepresence in the physical states of a computer via the transformation that maps those states to a given *virtual environment.*

These ideas are subtle and it is useful to develop some fundamentals before going into more depth.

1.2 Overview of the Paper

The remainder of the paper is presented in two main parts. In Sections 2–4 the fundamental ideas are systematically developed, leading to a detailed presentation of the subjective telepresence test. In Sections 5–8 the transformations are developed and a practical subjective telepresence test is described. A conclusion is presented at the end in conjunction with a discussion of future work.

Part I: Fundamentals

2 Telepresence

Formally define telepresence as the case where *a person is objectively present*[5] *in a real environment that is physically separate from the person in space.*[6] Within this

5. Objective presence is formally defined in Section 3.1.

6. A more general definition of telepresence might include nonhuman operators. For example, one might wish to consider dolphin telepresence or even computer telepresence. Only *human* telepresence is discussed in this paper, however. Very little is sacrificed at this time by restricting the study to people. The restriction also frequently adds to the clarity of discussion.

general definition many different types of telepresence may be defined based on the type of objective presence. Indeed, the general definition is incomplete without further specification unless one is referring to *all* types of telepresence.

This is a broader concept than existing definitions of telepresence because it includes cases where the person does *not feel present* in the given environment. No doubt common usage of the term will continue to imply subjective aspects of telepresence. Technical discussions require more precision, however, and a major goal of this paper is to begin to develop the formal language required to state the type of telepresence explicitly.

Types of objective presence that may be used to specify the type of telepresence are formally introduced in Section 3. First, however, it is useful to present some basic telepresence concepts.

2.1 Teleoperation

Teleoperation is the only known way that telepresence might be achieved and it is convenient to use the associated terminology. Figure 2 identifies the four major functional components of teleoperation: (1) *human operator,* (2) *operator interface,* (3) *teleoperator,* and (4) *remote environment.*[7] In the following discussion an *operator* is considered to be anything that is capable of causing or detecting an event. The human operator is a person who uses the *teleoperation system* (consisting of the operator interface and the teleoperator) to control and/or sense events in the remote environment. The teleoperator (nominally a machine) functions as a surrogate for the human operator in the remote environment.

The operator interface is the physical interface between the human operator and the teleoperator. Nominally this includes *displays* that provide sensory input to

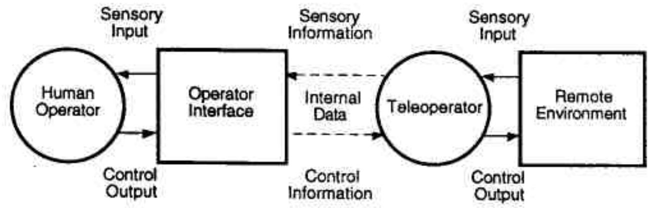

Figure 2. *Major functional components of teleoperation.*

the human operator and *controls* that the human operator uses to provide information to the system.[8] The remote environment is a *real* environment that is physically separate from the human operator in space.

These components are consistent with definitions proposed by Sheridan (1992a, 1992b). Many examples of teleoperation are described by Vertut and Coiffet (1986).

2.2 Virtual Presence

Virtual presence corresponds to telepresence where the teleoperator and the remote environment are simulated inside a computer. In this case the human operator's mental representation of the remote environment is commonly called the *virtual environment.* An excellent survey of the area is provided by Ellis (1991). The argument that virtual presence is formally a type of telepresence is presented in Section 7.4 after the necessary foundation is laid.

2.3 Miscellaneous Terminology

A *telepresence system* (of a given type) is a teleoperation system that makes telepresence (of the given type) *possible.* When the human operator actually has the desired type of objective presence in the remote environment it may be said that he or she is *telepresent.* Equivalently, in the case of subjective types of telepresence (for example, where the human operator *feels present* in the remote environment) one might say that the human operator is *experiencing* telepresence.

7. Figure 2 illustrates the most interesting case of teleoperation where the teleoperator and the operator interface are physically separate except for an interconnecting communication system. The communication system is not formally identified in the figure, but is indicated by the dashed arrows. The figure also neglects the possibility of direct communication between the human operator and the remote environment. There are, of course, many examples of teleoperation where the operator interface and the teleoperator are not physically distinct and/or where there is direct communication between the human operator and the remote environment. One example of both situations is a stick being used to poke coals in a fire.

8. Both the operator interface and the teleoperator may include subsystems that transform and/or feed back some of the information flowing back and forth between the human operator and the remote environment. For example, in the case of *supervisory control* (Sheridan, 1992b) the teleoperator may perform simple tasks independently.

2.4 Telepresence Performance

The *telepresence performance* of a telepresence system is a measure of the system's ability to make the human operator telepresent. It is defined as the *degree*[9] of objective presence of a 50th percentile human operator who is using the system.

3 Presence

Physical presence is defined here as the *existence* of an *object* in some particular region of *space* and *time.*[10] For example, this text (in some form) is physically present in front of you now.

Physical telepresence is impossible by definition: a person cannot be physically present in an *environment*[11] that is physically separate from the person in space. A more general type of presence that is suitable for the analysis of telepresence may be defined, however, based on one aspect of physical presence. Specifically, objective presence is defined based on causal interaction.

3.1 Objective Presence

An operator is objectively present if and only if it can successfully complete a specified task.

3.1.1 Example. Consider the task of *throwing the ball into the basket.* It is assumed that some particular basket, ball, and manner of throwing are specified. If a person (the operator) can throw the ball into the basket when asked to do so, then he or she is objectively present *in the task.*

3.1.2 Type. The most important thing to observe about objective presence is that it depends on the *specified task* in a fundamental way. In general, the same operator will be objectively present for one set of tasks and not objectively present for another set of tasks. This fact provides a means of identifying different types of objective presence. Specifically, the type of objective presence is defined by the set of specified tasks.

3.1.3 Degree. The degree of objective presence is defined to be the probability that the specified task is completed successfully. For example, suppose that in the previous example the person is able to throw the ball into the basket only half of the time. In that case the person's degree of objective presence is ½.

Alternative definitions of the degree of objective presence are also possible. Indeed, any performance measure will work in a specific case. This paper focuses on probability because it appears to be the most general way of looking at the problem.

3.1.4 Expected Value. The degree of objective presence may be used to define an overall measure of operator performance for a set of tasks with multiple outcomes. The measure is the *expected value* of the operator's performance, given by the following equation (assuming a discrete set of outcomes):

$$\nu(x, \tau) = \sum_{t \in \tau} \mathbf{P}_t \left[\sum_i \mathbf{P}_{xit} \mathbf{V}_{it} \right]$$

where

$\nu(x, \tau)$ = expected value of performance of operator x for a given set of tasks τ

$\mathbf{P}_t$ = probability of task t

$\mathbf{P}_{xit}$ = probability that outcome i will occur given task t is performed by operator x (i.e., the degree of objective presence)

$\mathbf{V}_{it}$ = value of outcome i given task t.

To use the measure one must define a value function, $\mathbf{V}(i,t)$, over the space of all possible operator events.[12] In

9. The degree of objective presence is formally defined in Section 3.1.3.

10. The primitive concepts *existence, object, space,* and *time* are not formally defined here, but I assume that the reader has a working knowledge of these terms.

11. The terms *environment* and *region* will be used somewhat interchangeably in the paper, although there is a subtle distinction. The *American College Dictionary,* 1963, Random House, defines environment as "the aggregate of surrounding things, conditions, or influences." Region, on the other hand is defined as "any more or less extensive, continuous part of a surface or space." Physical presence in an *environment* thus has to do with being one of some set of objects, where the set of objects exists is some *region* of space.

12. This is in contrast to the notion of expected utility in decision theory where it is assumed that a person uses a utility function in making a decision (von Neumann & Morgenstern, 1947; Adams, 1960). While the two ideas have much in common, in decision theory the utility function must be determined. Here, on the other hand, the value function is simply part of the task definition.

other words, a real number, $\mathbf{V}_{it}$, corresponding to some interval scale of value is assigned to every possible outcome i of every task t. Note that the *value* of an outcome might be either positive or negative.

The idea is that the value function *defines* the measure of performance so that, for example, $v(x,\tau) > v(y,\tau)$ means that *on average* operator x performs *better* than operator y for the given set of tasks. Similarly, one can define a reference value, $\mathbf{V}_{ref}$, such that $v(x,\tau) > \mathbf{V}_{ref}$ means that operator x is *useful*. In the case of individual outcomes, of course, the measure of performance is simply the value of the outcome.

3.1.5 Application to Telepresence. Telepresence is *measured* by defining the type and then measuring the degree of objective presence (or the expected value in complex cases). More work is required to identify important types of objective presence in the study of telepresence. This paper deals with only a single, albeit important case related to a person's *feeling of presence*.

3.2 Subjective Presence

A person is subjectively present in some particular environment if and only if the person perceives that he or she is physically present in that environment.

3.2.1 Example. Define for yourself some environment where you perceive that you are physically present. For example, you might look around and see that you are in a particular room in a building. In that case you are subjectively present in that room.

3.2.2 Type. Subjective presence is itself a general type of objective presence. The general *task* is for the person to perceive that he or she is physically present in the specified environment given some control/sensory interaction. Subtypes of subjective presence may, in turn, be defined based on transformations of the general task. For example, subjective presence is different when the person's eyes are closed rather than open. Before going into such refinements, however, one should understand the basic concepts. Transformations are discussed in Sections 5–8.

3.2.3 Degree. Consistent with the degree of objective presence, the degree of subjective presence is defined to be the probability that the person perceives that he or she is physically present in the given environment. For example, in the previous example there might be only a 50% chance that you would recognize that you are in the given room (presumably because it looks very much like another room). In that case your degree of subjective presence *in the given environment* is ½.

In general, degrees of subjective presence exist because perceptions are based on ambiguous sensory input.[13] Specifically, the degree of subjective presence depends on how certain the person is that his or her control/sensory interaction with the world is the result of physical presence in the given environment. The situation is described by the theory of signal detection where perception is modeled as a decision[14] between alternate hypotheses (Swets, Tanner, & Birdsall, 1964, p. 54). In the case of subjective presence the person's decision is between (1) being physically present in the given environment, or (2) *not* being physically present in the given environment, i.e., being in some other environment.

The key contribution of signal detection theory is to recognize that perception (and hence the degree of subjective presence) is affected by two independent factors: *sensitivity* and *bias*. Sensitivity is a measure of the person's ability to distinguish between different stimuli, while bias is a preference for one hypothesis over the other, unrelated to the physical stimuli. In general, bias is related to the level of certainty that a person requires in order to select a given hypothesis. See Green and Swets (1988) for a detailed presentation of the theory.

3.2.4 Operational Definition. Measuring the degree of subjective presence is more complicated than for other types of objective presence because it is not possible to observe another person's perceptions di-

13. For the record, Richard M. Held (Professor Emeritus and Senior Lecturer in the Department of Brain and Cognitive Sciences at the Massachusetts Institute of Technology) has told me on many occasions that it is the fact that perceptions are based on ambiguous sensory input that makes telepresence (where a person feels present in the remote environment) possible.

14. In an experiment the detection of a signal by a human observer often involves a conscious choice, however, in the case of perception the "decision" is a subconscious process.

rectly. Such observations are a fundamental problem in psychology and are the province of the scientific discipline called psychophysics (Gescheider, 1985). Signal detection theory is an important tool of psychophysics used to distinguish the relative effects of sensitivity and bias.

Definition. The most obvious way to find out about a person's perceptions is to ask. Consider the following procedure that will serve as an operational definition of the degree of subjective presence:

1. Set up a test where a person must make a series of observations under identical conditions.[15] During each observation the person is required to interact with the world in some manner and to determine his or her location based on the interaction.
2. Specify a single environment for the test and, during each observation, ask if the person perceives that he or she is physically present in the specified environment.[16] If the person says, "yes," then he or she is subjectively present in the specified environment on that trial of the test.
3. The person's degree of subjective presence in the specified environment is estimated from the relative frequency of "yes" responses for a large number of trials.

Discussion. A single experiment might involve multiple test conditions as in the example presented in Section 1.1.1 where a person stands at different locations and judges whether he or she is inside a room. When there are multiple test conditions, the operational definition is applied to each condition independently and a separate degree of subjective presence is measured in each case. Specifically, if there are n test conditions then n degrees of subjective presence are estimated; where the ith degree of subjective presence is equal to the conditional probability, $P(\text{"yes"} \mid C_i)$, that the person says "yes" (I perceive that I am physically present in the specified environment) when the ith test condition (C_i) is presented. The degrees of subjective presence are, of course, measured for the person who is taking the test and are always with respect to the same specified environment.

Naturally, the results of the test may vary significantly depending on the experimental conditions. For example, in the hypothetical experiment of Section 1.1.1, a more abrupt transition between all "yes" and all "no" responses might be observed if the person is given some means of determining his or her position more precisely (i.e., if the sensitivity is increased). Alternatively, one might cause the psychometric function, at the top of Figure 1, to shift to the right by instructing the person to say "yes" only when he or she is ***absolutely certain*** of being in the room (i.e., by changing the person's bias). In general, the test conditions can affect both sensitivity and bias, and one must take both factors into account in order to understand how a person's degree of subjective presence is related to his or her control/sensory interaction with the world.

Ultimately, however, it is also important to remember that subjective presence is *subjective.* In one case a person might have a high (or low) degree of subjective presence because he or she accurately detects (or does not detect) physical presence in the specified environment. In another case the person might simply have a strong preference for saying "yes" (or "no") in the experiment. Either way the operational definition measures the degree of subjective presence.

15. The simple fact that one observation is made after another means that they can never be absolutely identical, however, I assume that the conditions can be made sufficiently similar for the purposes of the test.

16. In many cases it is convenient simply to ask the person, "are you in the specified environment?" In other words one asks what the person ***believes*** about where he or she is physically present. In such cases one assumes that the test is arranged so that the person ***believes*** that he or she is in the given environment because he or she ***perceives*** this to be the case. Perception and belief need not correspond of course. For example, in the Muller-Lyer illusion (Goldstein, 1989, p. 12) two lines appear to be different lengths even when you ***know*** that they are the same length. Subjective presence is defined in terms of what the person perceives.

4 Subjective Telepresence

Subjective telepresence may be defined in the language of teleoperation as the case where *the human operator is subjectively present in the remote environment.*[17] The following test *illustrates* how the operational definition of subjective presence may be used to measure the degree of subjective telepresence. More efficient psychophysical procedures, such as a direct subjective rating, may be possible in practice.

4.1 Subjective Telepresence Test

Consider a yes–no psychophysical procedure (Gescheider, 1985, pp. 113–116) where a human test subject must choose between two cases: **N** and **T**. Define the two cases and the subject's two possible responses as follows:

Test Cases:

N = the *nominal* case where the subject is interacting directly with the environment where he or she is physically present.

T = the *transformed* case where the subject (human operator) is interacting with some remote environment via a teleoperation system.

Responses:

"N" = the subject responds, "it is case **N**." This is equivalent to the subject saying, "I am physically present in the test environment."

"T" = the subject responds, "it is case **T**." This is equivalent to the subject saying, "I am *not* physically present in the test environment."

Assume that when the subject responds that he or she is (or is not) physically present in the test environment, it is because he or she perceives this to be the case. Specifically, assume that both cases are possible and that the subject *cannot* detect any difference between the environments of **N** and **T** when he or she is physically present in them. For example, it might be the same inhabitable region in space (see Fig. 3).

Also assume that the experiment is constructed so that when the subject is asked to choose, he or she does *not* have prior knowledge about whether it is case **N** or **T** beyond the a priori probability. The fact that this is possible may be seen by considering the following procedure (suitable for thought experiments):

1. prior to each trial, put the subject to sleep,
2. connect the subject to the teleoperation system (or not) at random,
3. awaken the subject and ask the question, "is it case **N** or **T**?"

The test would involve a large number of such trials for a fixed set of test conditions. A complete experiment might then be made up of a set of tests, where different test conditions would be used so that the degree of subjective telepresence could be measured as a function of the controlled variable.

4.1.1 Analysis of the Test.

In general, the results of such an experiment can be summarized by using the data to estimate the probabilities:

P("N"|**N**) = the probability of responding "N" when the stimulus is **N**.
= the degree of subjective presence when the subject is physically present in the test environment.

P("N"|**T**) = the probability of responding "N" when the stimulus is **T**.
= the degree of subjective telepresence in the test environment.

The difference between P("N"|**N**) and P("N"|**T**) is related to the subject's sensitivity (i.e., the ability to distinguish between stimulus **N** and stimulus **T**). While the overall level of these two quantities is related to the subject's bias (i.e., the tendency to respond "N" independent of the stimulus). Readers interested in detailed quantitative methods and the underlying assumptions for computing sensitivity and bias are referred to the

17. This definition is simply a restatement of the formal definition presented in Section 2 for the particular type of telepresence.

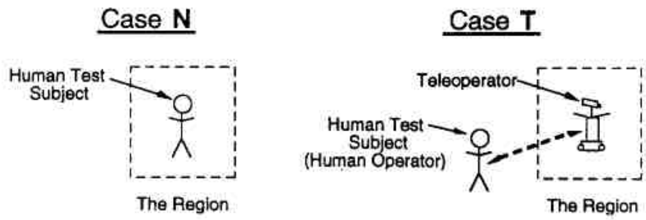

Figure 3. *Illustration of cases* **N** *and* **T.**

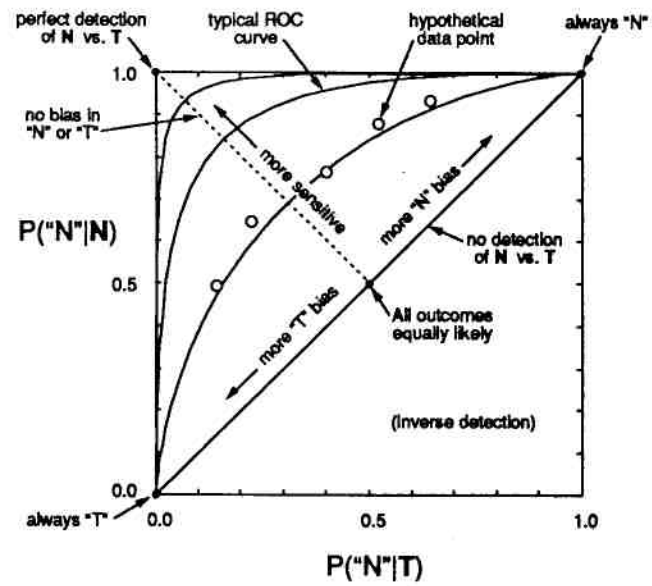

Figure 4. *Expected results for a subjective telepresence experiment based on the theory of signal detection.*

literature on signal detection theory. See Falmagne (1986) for an overview and an up-to-date list of references.

Figure 4 illustrates the type of results expected for a subjective telepresence experiment based on the theory of signal detection (Gescheider, 1985; Green & Swets, 1988). Hypothetical data points are plotted in the figure corresponding to a set of tests where the test subject is caused to change his or her bias while other test conditions remain constant. This might be accomplished, for example, by controlling the value (or cost) associated with the subject's choice (Gescheider, 1985, pp. 78–80). Plots of $P(\text{"N"}\,|\,\mathbf{N})$ vs. $P(\text{"N"}\,|\,\mathbf{T})$ derived in this way are often referred to as receiver operating characteristics.

Different receiver operating characteristic (ROC) curves are shown in Figure 4 corresponding to a range of sensitivities.[18] The curves might correspond to different test subjects who have different abilities to distinguish **N** from **T**. Alternatively, each curve might correspond to a different teleoperation system. Indeed, it may be desirable to use the sensitivity of a 50th percentile human operator as an ***unbiased*** measure of subjective telepresence performance. Note that the unbiased subjective telepresence performance is inversely related to sensitivity such that the ROC curve for the system with the *best* performance would be closest to the diagonal line running between (0,0) and (1,1).

18. The ROC curves shown in Figure 4 are representative only of the type of results that would be observed. The curves were calculated based on the assumption that the probability density functions for N and T are Gaussian with equal variance. Other distributions are possible, leading to ROC curves with different shapes (Green & Swets, 1988).

4.1.2 Normalized Degree of Subjective Telepresence (T_s).

The normalized degree of subjective telepresence, T_s, is defined to be

$$T_s = \frac{P(\text{"N"}|\mathbf{T})}{P(\text{"N"}|\mathbf{N})}$$

This measure is simply the degree of subjective telepresence, $P(\text{"N"}\,|\,\mathbf{T})$, normalized to correspond to the case where the human operator is always subjectively present in the remote environment when he or she is physically present there. Nominally, T_s ranges from zero (when the subject can always detect the difference between the two cases of the test) to one (when the subject is just as likely to respond "N" when it is case **T** as when it is case **N**). In other words $T_s = 0$ when the subject can always detect that he or she is using the teleoperation system. And $T_s = 1$ when the subject is just as likely to respond, "I am physically present in the test environment," when he or she is telepresent as when he or she is physically present in the environment.

The principal advantage of normalization is that it accounts for an inherent bias of the subjective telepresence test. Specifically, the test biases the subject away from *always* responding either "N" or "T" regardless of his or her sensory experience. This is so because the subject is unavoidably aware that either **N** or **T** might be presented during a trial. T_s does not eliminate all bias, of course, as it should not: a person may be more (or less) subjectively telepresent depending on his or her bias toward (or away from) perceiving physical presence in the remote environment.

There are two apparent problems with T_s. The first problem is that the ratio is undefined for $P(\text{"N"}|\mathbf{N}) = 0$. This is precisely what one should expect, of course, because the proposed measure is based on the assumption that a person can detect physical presence. If $P(\text{"N"}|\mathbf{N}) = 0$, then the test subject *never* says that he or she is physically present in the test environment when, in fact, he or she *is* physically present there. This means that the subject is unable to correctly detect physical presence during the test. This, in turn, makes any detection of physical presence when the subject is using the teleoperation system meaningless.

The second apparent problem is that values of T_s larger than one may be observed in a test. This might occur for two reasons. First, it is possible for the observed ratios to differ from the true probabilities because there are only a finite number of trials in the test. Consequently, statistical fluctuations are likely to give a result where $P(\text{"N"}|\mathbf{N}) < P(\text{"N"}|\mathbf{T})$ when the true probabilities are approximately equal. I do not consider this to be a serious problem because $T_s = 1$ still corresponds to *perfect* subjective telepresence. Observations where $T_s > 1$ are simply experimental error.

A second reason T_s might be greater than one is that the subject, while able to detect the difference between **N** and **T**, may interpret some perceptions incorrectly. For example, the subject may consistently respond "T" when he or she perceives a certain stimulus associated with **N**. Again, as in the first case, $T_s > 1$ does not imply that the human operator is more telepresent than when $T_s = 1$. Indeed, one could argue that the human operator is less telepresent in the second case. I believe that the best approach here is to repeat the test after further training of the subject. With sufficient training it should be possible to reduce the value of T_s to less than or equal to one.

4.2 Subjective Virtual Presence Test

The subjective telepresence test may be used directly to measure subjective virtual presence. In the case of virtual presence, the environment of case **N** is a physical environment that corresponds to the virtual environment. In other words, the physical environment of case **N** is the environment that one attempts to simulate in case **T**.

Part II: Transformations

5 Apparent Problems with the Test

The previous sections neglect two significant problems with the subjective telepresence test. First, it appears that no existing teleoperation system is likely to pass it! This is a serious problem because it implies that there is no such thing as a subjective telepresence system (nor is one likely to be built in the foreseeable future). Second, the test only appears to apply to environments where it is possible for the human operator to be physically present.

There are, of course, many applications where it is desirable to interact with environments that are uninhabitable. For example, one of the major reasons for using a teleoperation system is to allow people to work safely in hazardous environments. In such cases one does not want subjective telepresence to include *all* aspects of the remote environment. Specifically, one does not want to communicate hazards to the human operator and, in general, one would like to be able to think about kinds of telepresence where transformations of the remote environment are allowed.

5.1 The Solution

The solution to these problems lies in the fact that new types of objective presence (and hence subjective telepresence) may be defined by transformations. Specifically, recall that a type of objective presence is defined by a specified task. A transformation may be thought of as a modification of the task and any type of objective presence may be divided into subtypes where the operator performs the original task with and without the specified transformation.

In general, transformations are simply another means of partitioning the set of all possible tasks. Thus, one can speak of types of objective presence (and hence subjective telepresence) corresponding to particular transformations or sets of transformations.

Two general transformations are discussed in the following sections: (1) *control/sensory transformations* imposed on a person's interaction with the world, and (2) *transformations of the region of presence.* Types of subjective telepresence defined by these transformations are achievable with existing technology. Types of subjective telepresence may also be defined for environments where it is not possible for the human operator to be physically present.

6 Control/Sensory Transformations

A control/sensory transformation may be defined as a modification of the causal relation between a person's intentions or perceptions and the corresponding events in the world. For example, a person might wear prism goggles that invert his or her visual field. The inversion is a control/sensory transformation.

6.1 Application to Subjective Telepresence

A teleoperation system imposes a control/sensory transformation on the human operator. Indeed, this transformation is the key determinant of the system's subjective telepresence performance. Other control/sensory transformations can also be imposed as part of a subjective telepresence test. The degree of subjective telepresence observed in the test depends on the overall (system plus test) transformation and, ultimately, one may simply study the relationship between the control/sensory transformation and the degree of subjective telepresence without regard to any particular teleoperation system.

Alternatively, one can think of imposing an additional control/sensory transformation in a subjective telepresence test as a means of defining a different type of test, or, equivalently, a different type of subjective telepresence. For example, one test transformation would be to block all of the test subject's senses except vision. The type of telepresence observed in such a test might be called visual subjective telepresence. This would be different than auditory or tactile subjective telepresence, for example, and one might measure different degrees of subjective telepresence in each case.

Theoretically, there is no limit to the type of control/sensory transformation that one might impose in a test. For example, a particular teleoperation system could introduce a certain distortion into the human operator's interaction with the remote environment (say the visual field is inverted). One type of test transformation would then be to cancel the distortion (perform a second inversion of the visual field on *only* the **T** cases of the test). This might be done in order to study other factors affecting the system's subjective telepresence performance.

Restrictions in the flow of information between the test subject and the operator interface appear to be the most important general type of control/sensory transformation in the study of subjective telepresence. Such restrictions would be imposed equally on both the **N** and **T** cases of the test in contrast to the example of the previous paragraph. One particularly important type of restriction may prove to be the case where white noise is added to the human operator's control output or sensory input like in a masking experiment. While this may prove useful for theoretical reasons, it is not clear how it might be implemented in general. Other types of restrictions are straightforward to implement however. For example, one type of restriction is to cover the test subject's eyes.

Such restrictions can be imposed independently of the teleoperation system so that the same test can be used in all cases; in other words, so that the same type of subjective telepresence can be investigated. It is also clear that as the flow of information is reduced it becomes more difficult for the test subject to detect a difference between the two cases (**N** and **T**) of the test. As a result it becomes easier for a given teleoperation system to make the human operator subjectively telepresent. Indeed, in the limit where there is no interaction between the test subject and the operator interface, any teleoperation system will pass the test, although it is not a very interesting type of subjective telepresence![19]

6.2 An Example of Transformed Subjective Telepresence

The extreme case, where there is no interaction between the human operator and the teleoperation system, suggests that some type of subjective telepresence can be achieved with existing teleoperation systems. As an example, consider a teleoperation system like the master–slave manipulators developed by Raymond Goertz for handling radioactive material (Vertut & Coiffet, 1986, pp. 25–27). With such a device the end effector of the slave manipulator reproduces the movements of the human operator's hand in a one-to-one fashion. The slave manipulator looks nothing like a human arm, however, at least not so that the human operator is likely to perceive that it is his or her arm. The end effector is also visually displaced from where the human operator expects to see his or her hand. As a result, the human operator of such a system normally does *not* perceive that he or she is physically present in the remote environment.

Now consider a transformation of the human operator's control output and sensory input where the remote environment is made dark except for a few strategically placed points of light. For simplicity's sake say that the transformation is such that the human operator sees one spot of light at the location of the end effector. Also assume that the human operator's visual field is transformed so that the spot of light appears to be on his or her hand.

Given this control/sensory transformation, it is very likely that the human operator would *not* be able to differentiate between a case (**T**) where he or she is using the teleoperator and a case (**N**) where the spot of light is actually on his or her hand. In other words the transformation would make the human operator subjectively telepresent. Of course, it would also be necessary for the human operator to hold the master manipulator in both cases and to avoid touching any objects in the remote environment. These additional restrictions are required in order to avoid kinesthetic or tactile cues that would allow the human operator to differentiate between the two cases. Any such additional restrictions are simply part of the overall transformation that must be imposed to achieve subjective telepresence.

7 Transformation of the Region of Presence

The general idea behind a transformation of the region of presence is that a person can perceive himself or herself to be in one environment while physically interacting with a different environment. Before a formal definition is presented, it is useful to expand the concept of transformation.

7.1 A More General View

A more general way to think of a transformation is simply as a modification of a given mapping between two sets. For example, in the case of a sensory transformation, one set is the set of events in the world and the other set is the corresponding set of perceptions. The given mapping is the nominal causal relation between the events and the person's perceptions of those events.

Ultimately, the situation may simply be described as different mappings between the two sets. In the example, the nominal causal relation of sensation is one mapping and other mappings are defined by the sensory transformations. Indeed, one can describe the nominal mapping as a *base* transformation. In other words, taking some nominal mapping as the base, any mapping may be identified by its corresponding transformation relative to the base.

7.1.1 Telepresence as a Transformation. Define the case where a person is physically present in some environment as the nominal mapping or, equivalently, as

19. In fact one might argue that when there is no causal interaction with the remote environment it is not telepresence at all. Nevertheless, I find it convenient to think of this situation simply as the trivial case where the task is to *do nothing*.

the base transformation. Then, the situation where the person is interacting with the environment via a teleoperation system may be defined by the control/sensory transformation imposed by the system. Specifically, a mapping is defined by the way the system transforms the person's control/sensory interaction with the environment.

Virtual presence may be described by breaking the control/sensory transformation into a ***virtual control/sensory transformation*** and a ***transformation of the region of presence*** as shown in Figure 5. Consider the following formal definition.

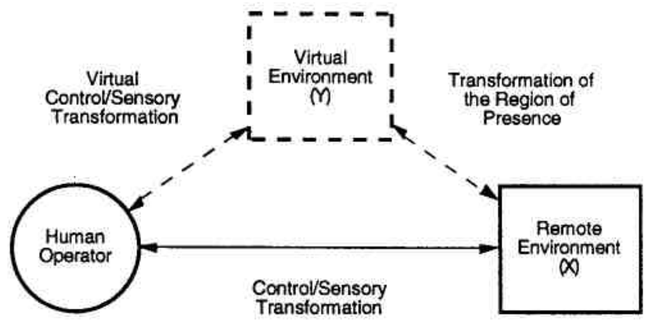

Figure 5. *Telepresence transformations.*

7.2 Formal Definition

Let X be a set of events and let Y be a set of events that is some specified mapping of X. Then objective presence in Y, or an environment defined by Y, may be considered to be objective presence in the set X via the specified mapping. *The specified mapping between X and Y is a transformation of the region of presence.*

7.3 Discussion

Two things need to be discussed before the definition is applied. First, the formal definition describes objective presence in terms of events rather than tasks (as defined in Section 3.1). Second, the meaning of subjective presence is unclear when the region of presence is transformed.

7.3.1 Tasks, Events, and the Region of Presence. A task may be defined in terms of a set of events. For example, consider the event: *the light goes on.* A person might be given the task of *causing* the light to go on. Correspondingly, objective presence *in the task* (of turning on the light) may also be called *efferent* objective presence *in the event* (of the light going on). Similarly, *afferent* objective presence in an event corresponds to the task of *detecting* whether or not the event occurs.

It is frequently simpler to describe types of objective presence in terms of tasks (rather than events) because the distinction between the efferent and the afferent cases is inherently part of the task description. Task definitions also ***describe how*** the given event is caused or detected and make it easier to discuss two-way interactions between the operator and the environment.

The advantage of describing objective presence in terms of events is that one can define a *region of presence.* Specifically, the region of objective presence may be defined as the environment where the specified event occurs.

7.3.2 Interpretation of Subjective Presence When the Region of Presence Is Transformed. In the case of *objective presence* it is not hard to imagine different kinds of transformations between a person and an environment. For example, consider a person in a room with an electrical switch. Assume that the person is capable of operating the switch and is able to observe its state. In other words, assume that the person is objectively present in the events: *switch on* and *switch off.* Now assume that the switch is connected to a light in another room such that the light is *always* on or off when the switch is on or off, respectively. Then, via the transformation (*switch on* = *light on*, *switch off* = *light off*) the person is objectively present in the events: *light on* and *light off.* In other words, the person is objectively present via a transformation of the region of presence.

Of course an experimenter testing the person's objective presence in the operation of the light would need to call the event, "switch on" or "switch off" for the person to understand. And the person would be objectively present in the operation of the light only as long as there was a causal link between the switch and the light. Nevertheless, a causal interaction between an operator and an environment is the essence of objective presence; transformation of the region of objective presence does not raise any philosophical problems.

I submit that the situation is no different in the case of subjective presence. For example, one might ask: where is a person subjectively present when he or she is interacting with a virtual environment that is simulated inside a computer? I respond that (1) the person is subjectively present in the virtual environment, and (2) the person is subjectively present (via a transformation of the region of presence) inside the computer; specifically, in the set of physical events defined by the changing states of the computer.

This interpretation simplifies the description of telepresence in environments where it is not possible for the human operator to be physically present. It is also perfectly defensible from a philosophical perspective. Specifically, it makes sense when one considers that even when a person is physically present in an environment there is some sensory/motor transformation (the base transformation).

Normally, one assumes that a person perceives the true physical form of an environment.[20] For example, a person perceives a chair because a *chair* exists in the real world. In other words, the base transformation is really a *null* transformation. But who is to say that a chair is a chair? Indeed, who is to say whether two people perceive the same object in the same way? While transformations can be normalized to the case where a person is physically present, there is no reason to prefer one transformation over another. Thus subjective presence in an environment via some transformation of the region of presence is just as valid as subjective presence in some other environment via the base transformation.

7.4 Virtual Presence

Given the ideas developed in this section, one can see that virtual presence is formally a type of telepresence as defined in Section 2. In both cases the human operator is interacting with a *real* remote environment. The remote environment of virtual presence consists of the changing states inside a computer. Indeed, it is the fact that the human operator is interacting with a real environment that makes virtual presence interesting. Without a real remote environment virtual presence would be nothing more than fantasy.

Clearly the human operator's perception of the remote environment is radically transformed in the case of subjective virtual presence, but such transformations are a fundamental part of the concept of telepresence being proposed. Thus, the unconventional view that virtual presence is a special case of telepresence is not due to any new way of thinking about virtual presence, but rather, it reflects a more general understanding of telepresence.

7.5 Subjective Telepresence in Uninhabitable Remote Environments

In general, given situations where it is not possible for the human operator to be physically present in the remote environment, it may still be possible to define types of subjective telepresence by a transformation of the region of presence. Specifically, if a corresponding physically realizable virtual environment can be found, then the subjective telepresence test may be performed using the physical counterpart of the virtual environment.[21]

In many cases the procedure would be straightforward. For example, the physical counterpart of a nuclear reactor might be an identical room without the radiation. In some cases, of course, it would be very difficult to construct the physical counterpart of the virtual environment for the subjective telepresence test. For ex-

20. Indeed Loomis (1992, p. 113), who discusses some interesting psychological and philosophical aspects of telepresence, begins his paper, "The perceptual world created by our senses and nervous system is so functional a representation of the physical world that most people live out their lives without ever suspecting that contact with the physical world is mediate."

21. Note that it probably does not make any sense to talk about subjective presence in virtual environments that are not physically realizable (at least in principle) given that subjective presence is the perception of physical presence. This is an interesting question, however, that might be explored using some type of subjective rating of subjective presence.

ample, virtual environments where one can walk through walls or ride on dinosaurs represent a significant challenge! Nevertheless, the subjective telepresence test would work for these cases in principle. For example, one might project holographic images of walls or construct robots that had the look and feel of dinosaurs. Clearly, however, an alternative procedure where the human operator simply rates his or her degree of subjective presence would be preferable in practice.

8 Example Subjective Telepresence Test

Figure 6 illustrates one type of apparatus that could be used for testing a servo-mounted television system with a head-mounted display. The apparatus consists of two identical test booths: a local booth and a remote booth. The subject, who is physically present in the local booth, wears the head-mounted display at all times. In other words the operator interface is part of the test transformation.

A pair of television cameras is mounted on the subject's head so that he or she can view the environment of the local booth via the head-mounted display. An identical pair of television cameras, mounted on a servomechanism controlled by the motion of the subject's head, is located in the remote booth. The arrangement is such that the subject is able to see either (**N**) the video output from the cameras attached to his or her head, or (**T**) the output from the servo-mounted cameras.

The subject's movements in the local booth are restricted by a box. Specifically, the box prevents the subject from either moving around the booth or from seeing any part of his or her body. The subject is able to physically interact with the environments of the two booths by manipulating a bar. The appearance and the motion of the bar are identical in the two booths.

Prior to each trial the experimenter would connect the desired output to the subject's head-mounted display at random, and without the subject's knowledge as to whether it is case **N** or **T**. Then the subject would be asked, "is it case **N** or **T**?"

It is not hard to convince oneself that, given sufficient restrictions, the situation could be achieved where the

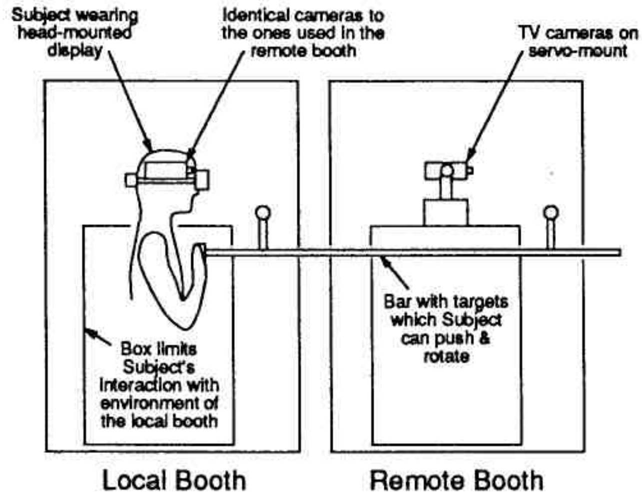

Figure 6. *Subjective telepresence test apparatus for a head-mounted display with servo-mounted TV cameras.*

subject would not be able to detect any difference between the two cases. Note that the restrictions, along with other conditions of the experiment, define the type of subjective telepresence that is being tested. Also note that the region of presence is not transformed in the test.

Once it is possible to achieve subjective telepresence, the performance of the system can be degraded so that the subject *is* able to detect a difference between the cases **N** and **T**. Hence, an experiment can be performed where some parameter of the system is varied and the normalized degree of subjective telepresence, T_s, is observed.

For example, assuming that the servomechanism can be modeled as a linear second-order system (Ogata, 1970) one could measure T_s as a function of the damping ratio, ξ. It is predicted that the subject would be subjectively telepresent ($T_s \approx 1$) for ξ near 1 (assuming it is possible to achieve subjective telepresence). Then, as $\xi \to 0$ or $\xi \to \infty$, it is predicted that $T_s \to 0$ since the servomechanism would either tend to oscillate ($\xi \ll 1$) or be sluggish ($\xi \gg 1$).

An experiment using one test subject would, of course, measure the degree of subjective telepresence only for that particular subject during that particular experiment. To measure the subjective telepresence performance of the system it would be necessary to test a representative population of human operators. Even when one is interested in only a single operator, it may be that the relationship between T_s and ξ, for example, changes due to various factors.

Beyond studying relationships between the degree of subjective telepresence and parameters of the system, one might also wonder how T_s depends on the types of tasks that are performed during the test, or on the types of restrictions that are imposed. Another question might be: how does T_s vary with some measure of task performance? Indeed, given a quantitative measure of telepresence, one is now faced with many questions.

9 Conclusion and Future Work

This paper presents a way of thinking about presence. Definitions are proposed that may be used to answer important questions about telepresence and virtual presence (which is shown to be a special case of telepresence). Two important questions are addressed in the paper. First, given a teleoperation system it is now possible to say whether the system is (or is not) a telepresence system *of a given type* and whether the human operator is (or is not) telepresent. Second, degrees of telepresence have been defined so that it is now possible to say whether one human operator is more or less telepresent than another. It is also possible to compare the telepresence performance of two systems. Together, the proposed types and degrees are the basis for a quantitative measure of telepresence.

Various research directions are open for the future. For example, a subjective rating procedure might be significantly easier to use than the test proposed in Section 4.1. More work is also required to identify important types of telepresence.

In general, while the type of telepresence can be defined precisely, there are an infinite number of different types. Precision is gained in the definition of telepresence at the price of complexity in specifying transformations and tasks. A significant problem with this approach is that different types of subjective telepresence are observed depending on the specific conditions of the subjective telepresence test. One is led to ask, is this really useful? The answer will depend on whether useful categories of telepresence can be defined.

Also, the comparison of different types of telepresence depends on the specification of a value function as described in Section 3.1.4. Unfortunately, determining the *value* of things is a philosophical problem that may never be resolved in a general way. As a result it may be difficult to apply the proposed measure of telepresence. For example, consider the following two cases. In case V, the human operator is always subjectively telepresent ($T_s = 1$) when sensory input is restricted to just vision. In case H, the human operator is always subjectively telepresent ($T_s = 1$) when sensory input is restricted to just hearing. Which is more telepresent, V or H? One would like to find some underlying principle that makes it possible to answer such questions in a rational way, at least in special cases.

Two other important questions that need to be addressed are as follows. First, what are the key parameters that affect the degree of telepresence? Information theory would suggest that information rate, channel capacity, coding, noise, and equivocation are all important. This area has only just begun to be explored.

Second, and perhaps most important, is telepresence useful? Clearly the usefulness of telepresence lies in the type of objective presence, in other words, in the tasks that can be performed. Subjective telepresence is useful, of course, when subjective presence itself is the goal, for example, in the case of an entertainment system. If subjective telepresence is to be considered a useful goal in other cases, however, task performance in the remote environment must be improved when the human operator is subjectively telepresent. What is the relationship between subjective telepresence and task performance?

In conclusion, it is clear that the theory presented here is only a first step. Success will depend upon whether it leads to answers that are useful and in agreement with experiment.

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