Psychological Theory in Haptic Interface Design: Initial Steps Towards an Interacting Cognitive Subsystems (ICS) Approach

Stuart Booth
Universita Degli Studi di Parma, Italy
E-mail: stuartandrewbooth@yahoo.co.uk

Thore Schmidt-Tjarksen
Universita Degli Studi di Parma, Italy
E-mail: tjarksen@igroup.org

Abstract

Haptic tasks call upon diverse processing resources within the human cognitive architecture. In order to develop appropriate interfaces it may, in consequence, be advantageous to adopt a holistic, psychologically based approach to its study. A candidate theory through which this might be achieved is Barnard's Interacting Cognitive Subsystems (ICS). ICS is a comprehensive theory of cognition and affect. It abstracts across the details of individual types of processing in order to permit a generic understanding of the systemic principles operating across the human cognitive architecture.

ICS is briefly described, followed by an example scenario, in order to illustrate how it might be applied to the understanding of haptic tasks. In addition, the structure of mental representations within individual types of processing is outlined. The importance of system-wide cognitive processes is considered before finally, an outline is given of the aims and objectives of the author's future work.

1. Introduction

Effective haptic interaction frequently requires complex cognitive activity on behalf of the user. For example, touch-based perceptions may be affected by various factors. These include stored high-level knowledge [1], the particular object properties sensed [2], availability of cues for object identification [3], perceptual bias by other modalities [4, 5, 6] and cross-modal attention [7, 8]. The sense of touch is, therefore, dependent upon diverse cognitive resources and, as a result, it may be useful to adopt a holistic, psychologically based approach to its study.

The present paper outlines initial steps towards the achievement of a holistic, haptic psychological schema, based upon Barnard's Interacting Cognitive Subsystems (ICS) [9]. ICS is a comprehensive theory of cognition and affect. It adopts a systemic approach in which information flows within a highly parallel and modular architecture of distributed cognitive resources. As behaviour arises out of the coordinated operation of its constituent parts, a major advantage of ICS is that cognition and affect can be considered within an overall psychological context, therefore making it ideally suited to inform reasoning about complex haptic interaction.

A brief outline of ICS will now be provided followed by a description of some of its implications for haptic processing. For a detailed description of the ICS architecture interested readers should refer to previous publications in which it has been outlined fully [10, 11, 12, 13].

2. ICS

ICS postulates nine subsystems, each of which differs in terms of types of information dealt with, level of representational abstraction and form of processing code (Figure 3). Although individual subsystems are associated with different types of subjective experience, they each share the same basic internal processing architecture, including a local memory (*Image Record*) and a number of parallel processes through which information is *transformed* from one form of subsystem code to another (Figure 1). This permits subsystems to operate together as a cohesive system. Behaviour results, therefore, from the flow of information through processing configurations within the overall cognitive architecture.

The transformations permissible have been derived systematically according to evidence available from experimental psychology and subjective plausibility (Figure 2). ICS has been applied within many theoretical areas including the understanding of depression [10, 11], mental number generation [14] and the analysis of cognitive processing in complex user tasks [15].

3. ICS and the haptic sense

ICS may be used to predict various mental and behavioural effects for users engaging in haptic tasks, with many implications for effective interface design. Most importantly, the model makes it possible to reason about the flow of information through the human cognitive architecture between sensation of a stimulus and production of a response. For example, if a user is presented with an apparently simple haptic task (such as to obtain as much information as possible about an unknown felt object) a characteristic flow of information processing may be predicted.

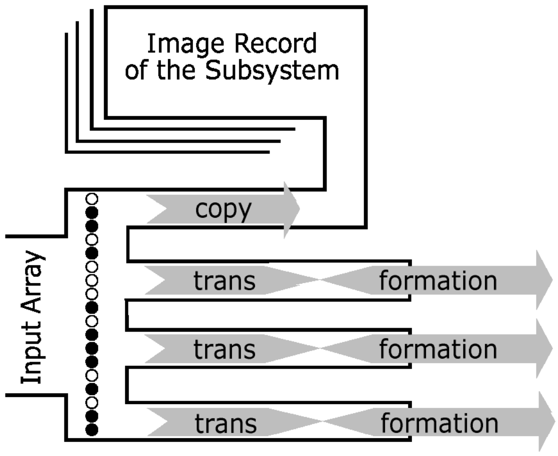

Figure 1. The internal architecture of an individual subsystem

3.1 Sensation and premotor action plans

Information will arrive within ICS via the bodily receptor organs at the BS (*Body State*) subsystem. Representations within BS are based upon information about the type of stimulation experienced (e.g. cutaneous pressure, temperature, muscle tension etc.), its location, intensity and so on. The resultant subjective experience takes the form of bodily sensations including pressure, pain and positions of parts of the body. Three parallel transformations from BS code to other types of subsystem code will then occur, two of which are central to the understanding of haptic experiences.

A transformation from BS to the LIM (*Limb*) subsystem produces representations based upon information about bodily forces, target positions and timing of skeletal musculatures. Subjectively speaking the experience is of 'mental' physical movement. Through the combined action of the BS and LIM subsystems it therefore becomes possible for a comparison to be made between actual bodily states and planned bodily states. Once executed as physical actions upon the world, the results can then be assessed through subsequent sensation, thereby forming a loop through which accurate bodily adjustments and readjustments may be achieved.

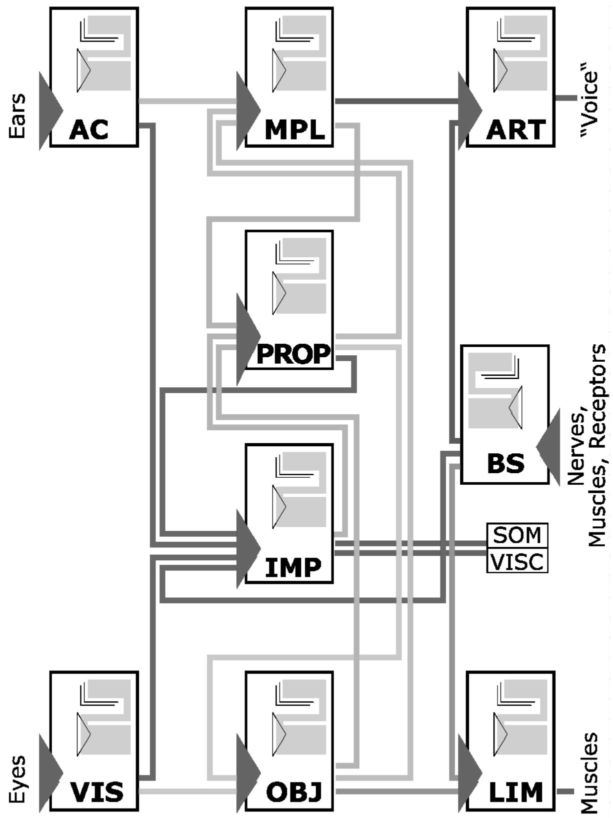

Figure 2. Schematic representation of ICS including the full range of permissible trans-formation processes (grey lines)

3.2 Sensation and high-level cognition

A parallel transformation from BS to the IMP (*Implicational*) subsystem results in schematic representations of sensory experience. For example, abstract ideational properties, such as surface 'hardness' or 'smoothness', may be subjectively experienced. It is, therefore, possible for haptic information to access the level of meaning in a relatively direct manner within ICS. The result may be an ability to use touch to categorise sensation within different types of schematic concepts. In order for the user to take advantage of haptic experiences in other ways, however, further processing is necessary in terms of transformations to other subsystems.

For example, a transformation from IMP to the PROP (*Propositional*) subsystem results in representations based upon semantic fact, the subjective experience being of

PERIPHERAL SUBSYSTEMS

a) Sensory

(1) Acoustic (AC):
Sound frequency (pitch), timbre, intensity etc.
Subjectively, what we 'hear in the world'.

(2) Visual (VIS):
Light wavelength (hue), brightness over visual space etc.
Subjectively, what we 'see in the world' as patterns of shapes and colours.

(3) Body State (BS):
Type of stimulation (e.g., cutaneous pressure, temperature, olfactory, muscle tension), its location, intensity etc.
Subjectively, bodily sensations of pressure, pain, positions of parts of the body, as well as tastes and smells etc.

b) Effector

(4) Articulatory (ART):
Force, target positions and timing of articulatory musculatures (e.g., place of articulation).
Subjectively, our experience of subvocal speech output.

(5) Limb (LIM):
Force, target positions and timing of skeletal musculatures.
Subjectively, 'mental' physical movement.

CENTRAL SUBSYSTEMS

c) Structural

(6) Morphonolexical (MPL):
An abstract structural description of entities and relationships in sound space. Dominated by speech forms, where it conveys a surface structure description of the identity of words, their status, order and the form of boundaries between them.
Subjectively, what we 'hear in the head', our mental 'voice'.

(7) Object (OBJ):
An abstract structural description of entities and relationships in visual space, conveying the attributes and identity of structurally integrated visual objects, their relative positions and dynamic characteristics.
Subjectively, our 'visual imagery.'

d) Meaning

(8) Propositional (PROP):
A description of entities and relationships in semantic space conveying the attributes and identities of underlying referents and the nature of relationships among them.
Subjectively, specific semantic relationships ('knowing that').

(9) Implicational (IMPLIC):
An abstract description of human existential space, abstracted over both sensory and propositional input, and conveying ideational and affective content: schematic models of experience.
Subjectively, 'senses' of knowing (e.g., 'familiarity' or 'causal relatedness' of ideas), or of affect (e.g., apprehension, desire).

Figure 3. The functions of the nine ICS subsystems (adapted from Barnard and May, 1995 [13])

meaningful statements about the sensory experience such as 'This is a hard, smooth surface'. Two further parallel transformations then occur. A link direct from PROP back to IMP results in reciprocal loops of processing between the two subsystems. As a result, meaningful thought becomes possible. Indeed, the transformation processes between PROP and IMP form the processing basis for many types of high-level cognitive tasks and their combined action is, therefore, termed the *Central Engine of Cognition*. Furthermore, representations of tasks themselves will be processed within IMP and PROP, thereby allowing representations (achieved through transformations from the senses) to be related to the active aims and goals of the perceiver. In the present instance the task may result in representations at PROP such as 'learn new things using touch' and, at IMP, categorizations of information as 'old' or 'new'. The two subsystems will, therefore, complement each other in decision making such that new information is processed and old information is not.

3.3 Visuo-spatial and auditory Imagery

In parallel with the initial transformation from PROP to IMP a second process also occurs to the OBJ (*Object*) subsystem. Here visuo-spatial representations become active, the result being mental imagery based upon PROP output. Whilst this may permit the activation of a mind's eye image of the felt experience, it is rendered indirect by the need to pass first through IMP and PROP after the initial BS representation. Information sensed via touch may, therefore, permit the achievement of effective visuo-spatial imagery but only *after* processing at the level of meaning.

In addition, a third transformation from PROP to the MPL (*Morphonolexical*) subsystem produces representations characterized in terms of auditory imagery and, in particular, that relating to speech. The subjective experience for the user will be of an 'inner voice' - an internal verbal dialogue based upon the output received from PROP. As conduction of the haptic task progresses this will serve as a subvocal commentary upon the state of the interaction. Via a transformation back to PROP representations processed at MPL may, in turn, influence the level of meaning. The user might, therefore, engage in an internal discussion with him/herself through the reciprocal action of MPL and PROP.

3.4 Stored information

Haptic processing is also dependent upon stored representations at each of the various subsystems involved. If incoming information matches or activates representations within the image record of a given subsystem, the data held within memory may be used to elaborate that derived from the immediate sensation, the result being relatively fast and detailed representations. If, however, stored representations are either unavailable or irrelevant, processing will be constrained to work upon the sensory input alone. In such circumstances haptic information will require increased processing time due to inherent restrictions on the degree of parallel processing its dedicated sense receptors are able to accomplish. In consequence it may be necessary to take advantage of a further transformation process from OBJ to LIM, the result of which being an influence of visuo-spatial imagery upon planned bodily movements. Once physically performed, the results of bodily actions can then be sensed, providing a loop between cognition and the sensory environment.

3.5 High-level cognition and premotor plans

A parallel transformation process from OBJ back to PROP ensures that visuo-spatially-based planned movements are not implemented without first taking into account the aims and objectives of the user. Representations at OBJ can, therefore, be transformed to factual statements at PROP and processed within the Central Engine of Cognition. Through comparison with representations of the currently active task, PROP can then feed-forward once more to OBJ which, in turn, influences planned movements at LIM. Actual physical behaviour is, as a result, strongly influenced by higher level meaning representations and, in consequence, the effects upon the sensory environment then become available once more to sensation, thereby allowing the whole process to begin again.

4. Implications

The above description of a touch-based scenario within an ICS framework suggests various implications for the development of effective haptic theory. The hypothesized processes operating within the BS and LIM subsystems validate the aim of many haptic researchers to understand low-level bodily sensations and pre-motor action plans. Importantly, however, ICS also highlights the need to consider more general cognitive processes, including high-level cognition and visuo-spatial mental imagery. Through its holistic approach the theory provides a means by which such analysis might be achieved. As described in section 3 this involves consideration of the processes operating between subsystems across the overall architecture. In addition, however, ICS also postulates generic principles upon which representations are structured within *individual* subsystems. In effect, therefore, although the types of data contained within each of the subsystems may differ, the rules by which their information is organized will be the same.

5. The structure of mental representations

Representations within individual subsystems have a hierarchical structure made up of various constituent items [16]. For example, an OBJ representation of a car dashboard may consist of the visual objects 'instrument display', 'steering wheel', and 'center consol'. Each item, in turn, consists of a group of further items one level down the representational structure. In the present OBJ example, therefore, the instrument display may consist of 'warning lights', 'speedometer' and 'revcounter'. Indeed, the hierarchical structure of the scene may extend through many representational levels down to the lowest possible discriminable unit. This is determined by the point at which further structural decomposition becomes impossible due to a lack of constituent items at the next level down the structure.

Within a representational structure the item that is the current focus of attention is referred to as the *psychological subject*. Through shifts in attention it is possible to change the subject to any item within a structure. There are, however, important constraints on the manner in which this may be achieved. For example, other items at the same level of structural decomposition as a psychological subject form its context. They provide information that is useful in discriminating the subject from other constituent items and are collectively referred to as its *predicate*. It is possible to make a direct *transition* of attention from a psychological subject to any of its predicate items so that a new subject is formed and the old subject becomes part of its predicate.

In addition, a subject and its predicate form the structure of the next item *above* in the representational hierarchy. Conversely, the items at the level *below* a psychological subject form its structural group. A single transition is required to move subject up or down a level in the representational hierarchy. Shifts of two or more levels, however, require changes through successive levels. If, therefore, in the OBJ representation of a dashboard, the psychological subject is shifted from the speedometer to the 'hazard warning light button' on the center consol, the transition 'path' must first move up a level so that the instrument display becomes the subject. The predicate of the instrument display will then include the center consol and so a further transition will be possible with the center consol as the new subject and the instrument display now part of its predicate. Finally, as it is now a constituent item within the group of items forming the center consol, the psychological subject can be shifted down the structure again to the hazard warning light button. Importantly, with each transition there is an associated cognitive cost. Complex transition paths therefore lead to high processing demands.

6. System-wide processing

The OBJ subsystem example is useful here because it permits illustration of the manner in which system-wide cognitive resources may be involved in haptic interaction. Say, for example, that the user must investigate our imaginary dashboard using a haptic device, with no other sensory input. In addition to the processing occurring within the BS and LIM subsystems, cognitive activity can also be predicted to occur within other forms of representation, including OBJ. Via transformations through the level of meaning (IMP and PROP), visuo-spatial imagery will be formed within OBJ with the representational structure described above. This may influence further haptic exploration as the user attempts to move his/her hand in line with this 'mind's eye image'.

The OBJ subsystem example has been developed here purely for illustrative purposes. It is, however, essential to understand that such structural principles form the basis of processing within all nine subsystems of ICS. The difference between types of representation is the kind of data dealt with and not the manner in which that information is processed. In principle, representational structures can be hypothesized for all of the subsystems involved in a given haptic scenario and it is, therefore, important for designers of haptic interfaces to consider system-wide cognitive processes.

7. Summary

The present paper deals with a limited range of haptic issues. ICS is not, however, restricted to a narrow array of applied contexts. Indeed, because the model underspecifies the details of individual types of mental processing, it is possible to use it to understand the complex cognitive processing occurring within various different instances, thereby enabling an ICS equipped interface designer to reason about most haptic situations.

In addition, it is possible to use ICS to make theoretical predictions about the effects of various changes to the interactive situation. For example, differences in task, changes in stimuli, the effects of other modalities, user expertise and knowledge, the availability of meaningful information, even the user's affective state, are all factors that can be reasoned about within its architecture. We are currently engaged in further work that attempts a comprehensive outline of ICS within the context of haptic interaction, together with empirical validation of the predictions of the theory and its practical implications.

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Figures 1 and 2 are based upon figures originally presented in Barnard and May (1995) [13].

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