Investigating Sensorimotor Contingencies in the Enactive Interface

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Abstract. Sensorimotor theories of perception have been widely investigated in the context of the perceiver's normal environment, but not in the context of virtual environments. There are clearly identified differences between perception of pictures and that of a real-world environment, but these differences have not been studied in the light of sensorimotor theory. Nagel et al.'s studies of sensory augmentation included a trial of their feelSpace belt in a computer-game environment, but with inconclusive results. We propose that the sensorimotor contingencies that apply in the context of a virtual environment are significantly different from those in the 'real world', and might account for the differences found between 'normal' and picture perception. Building on Froese et al.'s work on Enactive Interfaces, and on Visell's structure for sensory substitution, we consider how interfacing a sensory augmentation device with a computer game environment might provide the basis for fruitful research in this area.

1 Sensory Substitution, Augmentation and the Enactive Interface

In a paper of 2011, Froese et al. [1] propose a definition of an Enactive Interface (EI) as "a technological interface that is defined for the purpose of augmented sense-making". The authors see the interaction of sensory 'input' and active 'output' as two facets of the process of sense-making: "the activity by which an autonomous and adaptive agent maintains a meaningful relationship with its environment". Such sense-making emerges from goal-directed activity, not just as responses to stimuli. Thus an EI can be seen as "any piece of technology that is designed to permit its user to engage in additional modes of sense-making by enabling the goal-directed regulation of previously unavailable sensorimotor contingencies." Such devices are 'experientially transparent' ('ready-to-hand' in Heidegger's terminology), as compared with the 'cognitivist' approach to technological interface, in which "the user is forced to shift their attention to the abstract output of the device and must reason about what this output means for the course of action ... rather than being implicitly facilitated in perceiving what to do ...".

For Froese et al., the Enactive Interface encompasses what have been widely discussed as Sensory Substitution (SS) and Sensory Augmentation (SA), along

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with systems such as haptic interfaces, prosthetic and assistive devices, virtual reality (VR) systems, and many aspects of everyday human-computer interaction (HCI)[1].

Schmidmaier [2] gives an extensive overview of SS and SA systems, their technology, and the insights they provide into the workings of human perception albeit with a strong 'passive perception' flavour. He categorises historical and currently available systems according to the modality by which information is displayed to the user, and the modality of its source data. Thus, for example, Bach-y-Rita's TVSS is categorised as Tactile/Visual, whilst Nagel's feelSpace belt is Tactile/Spatial Awareness. EI devices need not be confined to 'high-tech' systems that most current research addresses. The blind person's white stick is recognised as an example of Haptic+Audio/Spatial Awareness SS [3]. Some authors include the Braille system of writing, and Sign Language for those with auditory impairment, as further examples [2,3]; some would go so far as to include writing itself as an Auditory/Visual EI [4](cited [2]). By a similar argument, a drawing or photograph can be understood as a Visual/Visual EI; an audio player as Auditory/Auditory, and cinema or TV as a combination of both. For any such device to qualify as EI, we should require it to "implicitly facilitate perception". For example, Nagel et al. [5] consider that 'subcognitive processing' occurs with their feelSpace device when the user is able to benefit from the signals provided without the expense of attentional resources. This is in line with Froese's distinction between EI and the 'cognitivist' view of technological interface as cited above.

Visell [3] presents a somewhat different review of tactile SS, relating it both to our understanding of human perception and to the development of Human Machine Interaction (HMI). He presents the following useful structure for SS:

> "Information about the environment is typically acquired from sensors corresponding to modality A, and the information is transduced into a set of signals x(t) that are subsequently digitized. The sensors can be physical devices or they may correspond to measurements in a virtual environment. A coupling device maps the sensed data x onto a set of signals y(t) for driving the actuators of the display. The actuated display presents the information to a human sensory modality B, which is eventually transduced and processed by the intrinsic sensory system of the body." (See Fig 1 below.)

Visell also notes: "One feature . . . that many have argued is crucial to the effectiveness of such systems is that the interaction loop is closed, through the affordance of user control over the position and orientation of the sensors, represented by the dashed lines in the figure." It is important not to see Visell's structure as relating only to the input side of an input/output (sensing/action)

[1] For the purposes of this paper, we shall use EI in this encompassing sense, but will continue to refer to SS, SA etc where the context requires the more specific reference–for example, when discussing a paper or proposition that relates only to the narrower concept(s).

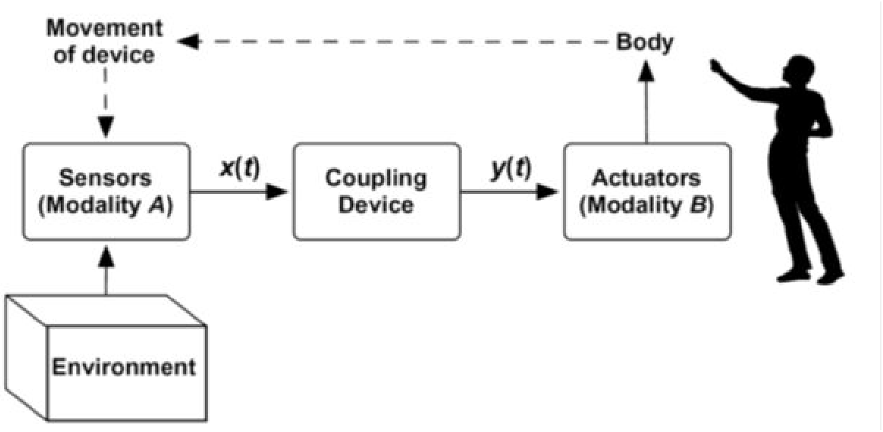

Fig. 1. Structure of a Sensory Substitution system (reproduced, with permission, from Yon Visell: Tactile Sensory Substitution: Models for Enaction in HCI [3])

system. 'User control' here should be understood to be an essential part of the user's active exploration of the environment – in EI terms, part of the process of active sense-making.

Visell's structure can readily be applied to the wider concept of EI, at least in the high tech examples. By specifying the mapping of digitized signals it would seem to exclude low tech systems; however, he also gives an alternative definition of SS as "the act of translating signals that are normally associated with sensory modality A to signals that can be detected via modality B". This definition applies equally well to the white stick as to its high-tech equivalent, the Enactive Torch (ET).

Table 1 shows how a range of EI systems would fit Visell's structure. As well as identifying the two modalities A and B, we have indicated where the sensors draw on a real or virtual environment, and distinguish between devices that aim to give experience of native and non-native modalities.[2]

2 Sensory Substitution and Augmentation in Perception Research

Sensory Substitution and Augmentation (SSA) is widely cited as offering support for Sensorimotor Theory of perception ([6,7,8,9,10]), as well as in more

[2] For this purpose we have categorised SS devices as delivering 'non-native' modalities: for example, the intended user of TVSS does not enjoy, as a native modality, the level of vision delivered by the device. However, we should note that there is no clear dividing line here, since blindfold sighted users, as well as users with a range of visual histories and of visual impairments, may all be included in trials of such devices.

Table 1. Examples of Enactive Interfaces, and how they fit into Visell's structure for SS devices

Coupling Device (Interface)	Nature of Environment (Real or Virtual)	Input to the EI (Modality A)	Actuators (Modality B)	Experienced Perceptual Modality	Control of Movement within Environment	Comments
Normal Perception	Real	All senses	All Senses	All native senses	Perceiver	Normal bodily movement
Still Picture	Virtual	Visual	Visual	Native Visual	None	
Moving Picture	Virtual	Visual	Visual	Native Visual	Device	Limited movement
Audio Soundtrack	Virtual	Auditory	Auditory	Native Auditory	Device	Limited movement
Interactive Game	Virtual	Visual, Auditory	Visual, Auditory	Native Visual, Auditory	Perceiver	Hand movements only, via mouse, keyboard, etc
Immersive Virtual Reality	Virtual	Multiple senses	Multiple senses	Multiple native senses	Perceiver	Full bodily movement
TVSS	Real	Visual	Tactile	Non-native visual	Perceiver	Limited movement (no eye movement)
Enactive Torch (also White Stick)	Real	Spatial	Tactile	Non-native spatial	Perceiver	Hand movements only
feelSpace	Real	Orientation	Tactile	Non-native orientation	Perceiver	Normal bodily movement
Computer assisted surgery	Real	Visual (Tactile?)	Visual (Tactile?)	Native Visual (Tactile?)	Perceiver	Normal bodily movement
Tactile Prosthesis	Real	Tactile	Tactile	Native Tactile	Perceiver	Normal bodily movement
feelSpace interfaced to Interactive Game	Virtual	Orientation	Tactile	Non-native orientation	Perceiver	Hand movements only, via mouse, keyboard, etc

conventional perception research (eg [2,3,10,11]). However, much experimental work in this area relies on uncontrolled small group or single case studies. Where controlled studies have been carried out, results have been more disappointing, and many speakers at a recent conference on SSA [10] concluded that evidence for phenomenal experience of the modality to be delivered by these devices just isn't there; some believing that such devices offer cognitive rather than perceptual experience[3]. On the other hand, it is notable that controlled studies (and, indeed, many small group studies) can measure their participants' use of the device under investigation in hours, usually over a study period of days or a few weeks ([1,5]); by contrast, what might be understood as genuine phenomenal experience of a delivered modality is repeatedly reported from the experience, often immersive, of single users over periods of months and years ([12,13]). It is also notable that, for visual SSA devices, there were considerable differences in the experiences obtained as between early-blind, late-blind and blindfold sighted users [10]. This raises the question as to how, and how much, each individual's previous perceptual experience influences the outcome of a trial. Again, there is significant difference between trials in the degree of directed training, as opposed to acclimatising experience, given to users ([1,5]). All of these factors make it difficult to draw any conclusions when comparing the outcomes of different studies.

This is clearly illustrated in Ward & Meijer's report [12] of the experience of a participant, PF, following immersive use of The vOICe auditory/visual SS device. PF, late blind at the age of 21, encountered The vOICe some 20 years later, and used it immersively from the age of 43. She reports that it took 3 months of immersive use "to learn enough so that I didn't have to consciously concentrate on it". Depth perception arose as "a kind of Eureka moment", after at least two months of "flat visual experiences of edges and shading". Five years later, she reported experiencing colour–which is not actually encoded by The vOICe: "Over time my brain seems to have developed, and pulled out everything it can from the soundscape and then used my memory to color everything". If a late blind user takes months to experience visual phenomenology, even with the benefit of remembered native experience, how much can we really learn from trials of only a few weeks?

3 Picture Perception – The Original Enactive Interface

We have argued above that pictures, in their various forms, satisfy the idea of an Enactive Interface. They also conform to Visell's structure for SS, which we have extended to apply to EI.

Just as Bach-y-Rita and Kercel saw writing as a kind of Visual/Auditory SS, so we might regard pictures as Visual/Visual EI. Froese et al. distinguish between devices that improve the function of an existing modality, such as spectacles for the short-sighted, and EI which should "enable the participant to generate and

[3] cf. Froese et al.'s distinction between 'cognitive' and 'enactive' technological interfaces.

make sense of qualitatively new forms of sensorimotor regularities". It might seem that this would not apply to a Visual/Visual device. However, Noë [6] has observed that:

> "Pictures construct partial environments. They actually contain perspectival properties such as apparent shapes and sizes, but they contain them not as projections from actual things, but as static elements. Pictures depict because they correspond to a reality of which, as perceivers, we have a sensorimotor grasp. Pictures are a very simple (in some senses of simple) kind of virtual space. What a picture and a depicted scene have in common is that they prompt us to draw on a common class of sensorimotor skills."

Note that we draw on a 'common' not an identical set of skills,. It is easy to see that some sensorimotor contingencies (SMCs) that apply in the real world, such as occlusion, parallax, looming etc, don't apply in a depicted image. In the more complex case of moving pictures (such as in film or in a first-person computer game), new contingencies come into play, as the images exhibit precisely these behaviours, but in relation to the camera or game character movement, rather than relative to any bodily movement of the observer. Furthermore, there is extensive research ([14]) into differences between 'normal' and picture perception–albeit from a conventional rather than a sensorimotor theoretical background.

Such differences include the duality of pictures, characterised variously as 'direct' and 'indirect' vision [15], 'twofoldness' [16] or 'conjoint representations' [17], whereby we see the picture both as an object in our natural environment, and its content as representing a different, virtual environment. These concepts of duality appear to have much in common with the distal and proximal perception of SSA; similarly, with Heidegger's three-fold concepts of 'ready-to-hand', 'present-at-hand' and 'unready-to-hand' in tool use; and with Froese et al.'s notion of transparency and opacity in the use of Enactive Interfaces. Cooper & Banks [18] and Sedgewick [19] discuss the distortions in depth perception that arise if we don't view a picture (in normal perspective) from its centre of projection. And Sedgewick [20] describes 'cross-talk' by which such distortions can be increased by emphasising features such as framing or surface texture that tell us we're looking at a picture.

And yet, there is a sense in which we do also draw on the contingencies of 'normal' vision, even when they don't apply in our picture. For example, in recognising a pictured object, we draw on the understanding of how its aspects (P-Properties, in Noë & O'Regan's terms) would change 'if I could move in relation to it within the depicted environment'. Thus the 'duality' of picture perception is, from a sensorimotor point of view, rather more complex. It seems that when we look at a picture, we may be exercising three different sets of sensorimotor skills–those applied to the picture as an object in our own environment; possibly some that apply only within the depicted environment; and those that would apply within the environment 'if I could move within it'.

It can be difficult to separate out these three sets. In the case of still pictures, it's not clear what contingencies could be specific to a depicted environment unless, for example, there are SMCs that account for the distortions of indirect vision. But in a moving (TV or cinema) image, we experience the contingencies arising from camera movement, even though we remain seated in one position. In the case of a first-person computer game, we have control of the character's movement, and therefore of the SMCs that arise–but not in the way we would in the real world, by walking around, turning our head etc; instead we control these contingencies by a very different set of hand movements to activate mouse and keyboard commands.

It is notable that we are very much unaware of all these differences. In discussing the importance of 'natural perspective' in our world, Hecht notes that much vision research is based on experiments using screen images, without any question as to their equivalence to 'everyday' visual perception.[4][14]. Pirenne [21] (cited [20]) suggests we may have an inbuilt mechanism to compensate for distortion due to looking at a picture from the wrong viewpoint–though Sedgewick queries whether such "a mechanism of formidable complexity" is likely to have evolved for the purpose of indirect perception alone. On the other hand, work with EI strongly suggests that whatever perceptual experience arises from these devices is a learned skill. In the developed world we have been looking at pictures (still or moving) almost as long as at the real world: perhaps it's just that these skills are equally transparent. With computer games, we may need to learn new manual skills, but these are applied to, and co-ordinated with, already transparent visual skills–though even here, there are some who experience 'visually induced motion sickness' (VIMS) ([22,23]). It might be instructive to look into responses to the new 3-D cinema technology, where there are clearly new contingencies to be learned, and where some viewers at least[5] find the experience distinctly uncomfortable.

4 Perception in Real and Virtual Space

We have seen that there are well-established differences between perception in the virtual space of still pictures and in our natural environment. It seems very likely that a similar range of differences apply to perception in more complex virtual environments, from moving pictures through computer games to immersive virtual reality. Research into picture perception has investigated these differences, primarily from the point of view of conventional perceptual theory, but no coherent picture has emerged as to why they arise. What new insight can sensorimotor theory of perception offer to this question?

We have suggested some ways in which visual SMCs do differ between particular virtual environments and the real world, and would predict that these should lead to phenomenal differences in perceptual experience. On the other hand,

[4] This practice may well arise from representational theories of perception: if visual perception is taken to be based on internal processing of a sequence of 'snapshot-like' retinal images–2-dimensional projections of 3-dimensional scenes–then it is easy to assume that seeing a snapshot is essentially the same as seeing its real world original.

[5] These authors included.

visual perception in both real and virtual environments is deeply ingrained in our experience, and the two are interrelated in such complex ways that it seems almost impossible to disentangle them. Looking at the broader field of Enactive Interfaces, it might be more fruitful to compare experiences that are both less well established, and in themselves less complex.

Table 2 offers a grouping of EI systems that suggests a way forward by making comparisons between categories on each dimension. Studies of picture perception have compared Native (visual) perception in Real and Virtual environments. SSA studies have focussed on Real environments, investigating the possibility of experiencing mainly visual and auditory perception as a Non-native, as compared with Native modality. However, two SSA devices in the Real/Non-native group relate to much less complex SMCs.

Table 2. Cross-tabulation of Enactive Interfaces on Real/Virtual vs Native/Non-Native dimensions

	Real (R)	Virtual (V)
Native (N)	Native perceptual experience of the real world–our normal mode of perception; also tactile prosthetics and systems such as computer-assisted surgery.	Native perceptual experience of a virtual environment, as exemplified by still and moving pictures, and by interactive computer games and immersive virtual reality.
Non-native (NN)	Non-native perceptual experience of the real world, as in SSA systems such as TVSS, feelSpace, ET and the white stick.	Non-native perceptual experience of virtual environment, as in Nagel et al.'s trial of their feelSpace device interfaced to a computer game.

Nagel et al., in their feelSpace trials, aim to deliver a non-native sense of spatial orientation[6]. Even though the team's later studies [25] suggest that users' phenomenal experience can be much more complex than simply knowing which way is north, the SMCs themselves are relatively straightforward: the tactile

[6] Awareness of directional orientation is regarded as a non-native perceptual modality in humans, but is native to some species of birds and animals who have a built-in ability to respond to the earth's magnetic field[5]. However Levinson [24] describes the aboriginal Guugu Yimithirr language group in Australia, who have no words in their language for egocentric concepts such as 'left', 'right', 'in front', 'behind', etc; instead, spatial references are made in terms of something very like our 'north', 'south', 'west' and 'east'. He notes that "GY speakers invariably seem to know, day and night, familiar or unfamiliar location, whether sitting still or traveling in a vehicle, where the cardinal directions lie." In the light of this extreme example, can we rule out the possibility that some individuals, whether consciously or not, can have a better 'sense of direction' than most, simply in response to everyday environmental cues?

sensation of the belt depends simply on the wearer's orientation about a vertical axis through the trunk. Froese et al.'s Enactive Torch (ET) also aims to deliver a form of spatial awareness, comparable to the blind person's white stick. SMCs here are less straightforward than feelSpace, but still much less rich than in visual perception, or even in Tactile/Visual or Auditory/Visual SS. Largely because of this relative simplicity, Froese et al. have proposed the ET as a "minimal EI" for the purpose of perceptual research [1].

Finally, in the Virtual/Non-native grouping, Nagel et al. have also reported on trials of using their feelSpace belt interfaced with a computer game environment [5]. Results were disappointing, but perhaps not surprising according to sensorimotor theory: differences in SMCs between the users' training in their Real environment and tests in the Virtual environment would readily account for this.

It would not be difficult to repeat Nagel et al.'s Virtual/Non-native trial using a suitably adapted feelSpace, ET or other comparable device; with training and tests all carried out in virtual environments delivering essentially the same SMCs. Assuming that some kind of subjective and/or measurable benefit is experienced in interacting with the virtual environment, the scene would then be set for further study in various directions. With suitable programming, variations in the environment, and in the way the device is used, can be investigated in a more controlled way than might be practicable in the Real world; users would have greater consistency in their non-experience of the proposed modality to be delivered; and the less complex nature of the modality might lead to shorter learning curves, which would make setting up controlled trials more practicable.

As well as studying a device and its usage within the Virtual/Non-native category, different EI systems may be compared both within and between categories. Such comparisons could shed light on the sort of problems we have discussed above. For example, differences and similarities between feelSpace in the real and virtual worlds (R/NN vs V/NN) may help us to understand the differences between direct and indirect vision (R/N vs V/N). Similarly, a comparison of feelSpace or ET experience against visual experience in the context of computer games (V/NN vs V/N) might suggest further lines of study as between SSA and normal perception (R/NN vs R/N). We offer some suggested lines of investigation using EI in a Virtual Environment, as follows:

Perceptual Experience

- Are there significant differences in experience as between using a system in the game environment and in the real world? (e.g. due to different SMCs arising from manipulating mouse/keyboard vs walking about)
- Is experience affected by delivery method: e.g. could feelSpace be worn (suitably scaled down) as a wrist strap, or as a Tongue Display Unit? Are skills transferable between these delivery methods?
- Are there differences in SMCs applicable to controlling first and third person characters? Would training in one context be immediately transferable to the

other? If not, what is the nature of the differences between them, and how would they effect subjective experience and/or measurable performance?
– Would we get the same sort of answers to the above questions for different types of device, such as feelSpace vs ET, in comparable game environments?

Training and Acclimatisation

– How much training and acclimatization are needed for benefits to be enjoyed? Is acclimatization sufficient without directed training?
– Are there factors in the virtual environment that might affect training requirements as compared with using the device in the real world? (e.g. is more or less training required? if so, why?)
– Are simpler modalities such as Spatial Orientation and Spatial Awareness easier to learn than, for example, visual/motor control of a character in the same environment?

5 Conclusion

The object of this paper was to explore the relationship between perception in the contexts of 'real' and 'virtual' environments, in the light of sensorimotor theories of perception, and particularly in the context of Enactive Interfaces; and to consider what sort of a device might be used to study this relationship empirically.

It is clear from the literature that research in areas such as picture perception has not yet taken much account of sensorimotor and related theories: the underlying assumptions of conventional 'snapshot' theories of perception are so well established that it is rarely found necessary even to mention them. Similarly, it appears that work done in picture perception has not always filtered through to research in EIs, although there is certainly some common ground. As a result, the unspoken assumption that images viewed on screen are processed in the same way as real world images is rarely challenged.

In attempting to pull together these different strands of research, we have proposed a classification of EI systems on two axes: whether the environment for perception mediated by an interface is 'real' or 'virtual'; and whether the perceptual modality delivered by the interface is native to the user or not. In the light of this classification, we have proposed that an SA device interfaced to a virtual computer game environment would offer scope for fruitful study. Such a device, classified as Virtual/Non-native, could be studied alongside comparable interfaces in other categories, such as the same SA device used in the real world (Real/Non-native), and the same computer game environment without the benefit of SA (Virtual/Native). It could be used both to pursue further work begun by others in the field, and to explore new avenues not yet studied. As a result, we anticipate that a valuable contribution can be made in drawing together research from a number of related areas whose work has so far tended to progress independently.

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