

Modeling the Multi-Sensory Design Space

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Abstract

Research into the visualization of abstract data has resulted in a number of domain specific solutions as well as some more generic techniques for visualising information. Similarly, the field of sonification has explored the display of information to the human auditory sense. As haptic displays such as force-feedback devices become more readily available, the sense of touch is also being used to help understand information. While applications that use multi-sensory information displays are becoming more common, frameworks to assist in design of these displays need to be developed. This paper extends a previously proposed structure of the visual design space to include hearing and touch and hence define a multi-sensory design space. It then correlates this space with another classification of the design space based on metaphors. Metaphors are often used as a starting point in designing information displays. Metaphors allow the user to take advantage of existing cognitive models as well as ecologically-developed perceptual skills. Metaphors provide another useful structuring of this multi-sensory design space. Throughout the paper all discussions are illustrated using the UML modeling notation. UML is a standard notation frequently used to document the design of software systems.

1 Introduction

Sometimes the ‘Information Age’ we live in would be better thought of as the ‘Data Age’. The widespread use of computer systems has seen a massive growth in the size of data sets available to analysts, designers, managers and engineers from many domains. These data sets can be characterised as abstract, multivariate and large. Data used for stock market trading, software analysis and marketing are three example domains but many more exist.

Whether the task is to understand or, alternatively to explore these data sets, many cognitive processes can benefit from the use of external models to support thinking. ‘Information Visualisations’ is the term commonly used to describe interactive computer systems

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that provide the user with external visual models of abstract data (Card, Mackinlay et al. 1999). Many approaches have been developed in this field to allow exploration of large multivariate data spaces.

‘Sonification’ is a newly evolving field, that uses sound rather than vision to represent abstract data (Kramer, Walker et al. 1997). Likewise, the term ‘Tactilization’ has been used when the sense of touch is used for displaying abstract data (Card, Mackinlay et al. 1999). This might better be called ‘Haptization’ as the word haptics refers to both the tactile and kinesthetic components of the sense of touch. Most interactions involving touch require a combination of both tactile and kinesthetic feedback.

Because some of the data sets being explored are so large and have so many attributes it has been proposed that multiple senses be used to analyze information in parallel. This requires the design of models that make use of multiple senses. ‘Perceptualization’ is the term that has been suggested to describe the multi-sensory display of abstract information (Figure 1)(Card, Mackinlay et al. 1999). Modeling the multi-sensory design space is the focus of this paper.

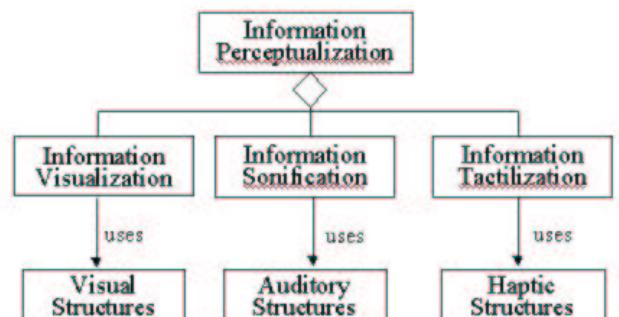


Figure 4. Information Perceptualization makes use of Visual, Auditory and Tactile Structures

The field of ‘Information Visualization’ has progressed largely by invention as applications are developed for specific domains. The field is disjointed as it brings together not only disparate application domains but all so many research areas. These research fields include computer graphics, information modeling, perceptual and cognitive science, human computer interaction and user interface design. Sometimes it seems that the design of an information display may be better described as an ‘art’ and not a ‘science’. Yet it would be desirable for non-

specialists to adopt an engineering approach to the design of information visualization. For example, to follow some simple guidelines and not have to understand complex perceptual theories beforehand or alternatively run time-consuming human factors experiments after the display is built. While this is true for designing visual displays it is even more critical when attempting to build a multi-sensory display where sensory interactions and conflicts complicate perceptual issues.

Categorizing the design space is an important step to assist in the development of general principles of design. Card and Mackinlay have proposed a taxonomy of the visual design space (Card, Mackinlay et al. 1999). This taxonomy is described and then extended in Section 2 to include auditory and haptic displays and so provide a categorization of the multi-sensory design space.

Another approach to understanding the design space is to consider how ‘metaphors’ have been used as a basis of information displays. Section 3 describes the motivation behind using metaphors in design and presents a taxonomy of the design space based on metaphors. The correspondence between the ‘Metaphor Design Space’ and the ‘Extended Card and Mackinlay Design Space’ is discussed.

2 Extended Card-Mackinlay Design Space

2.1 The Extended Process

Creating visualisations for a specific task is typically an iterative process of analysis, design and use. Card and Mackinlay describe this ‘Visualization Process’ (Card, Mackinlay et al. 1999) that maps from ‘Raw Data’ into ‘Views’. This process has been simplified in Figure 2 to show a more linear process from ‘Raw Data’ to ‘Data Tables’ to ‘Visual Structures’ and finally ‘Views’.

Figure 3 shows the extension of this process to include the design of multi-sensory displays. Visual structures are augmented by auditory and haptic structures (Figure 3). The word ‘haptic’ has been used because it refers to all the components that make up the sense of touch. Rather than the user seeing and interacting with a ‘View’ of the data they interact in a display which is multi-sensory. The type of display is dependent on the system but covers the range of emerging user interfaces that can be found in Virtual Environments. Many of these environments provide 3D visual, auditory and haptic displays [3,4,5].

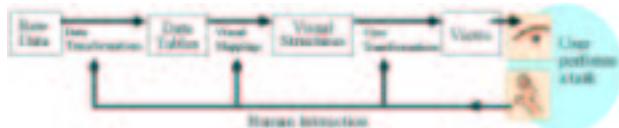


Figure 2. A process model for Information Visualization, adapted from Card-Mackinlay (Card,

Mackinlay et al. 1999)

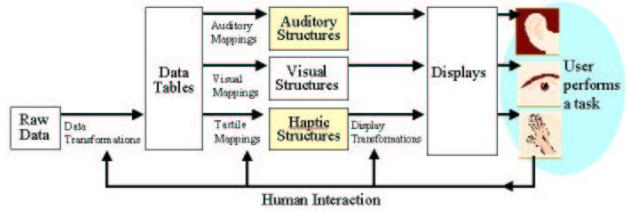


Figure 3. The process model extended to include multi-sensory displays. ‘Visual Structures’ have been augmented by ‘Auditory’ and ‘Haptic Structures’.

2.2 Raw Data

The multi-sensory extension (Figure 3) shows no changes to the initial part of the process. Raw data is still broadly characterized as *quantitative*, *nominal* or *ordered* as shown in Figure 4. Quantitative data may also be described in more detail if it has the intrinsic properties of being spatial, temporal or geographical. Raw data is transformed to a data table (Card, Mackinlay et al. 1999). Data tables place data attributes in rows and particular cases along columns of the data table (Card, Mackinlay et al. 1999). Data tables are more structured than the raw data and describe relations that can more easily be mapped into visual, auditory and haptic structures (Figure 5).

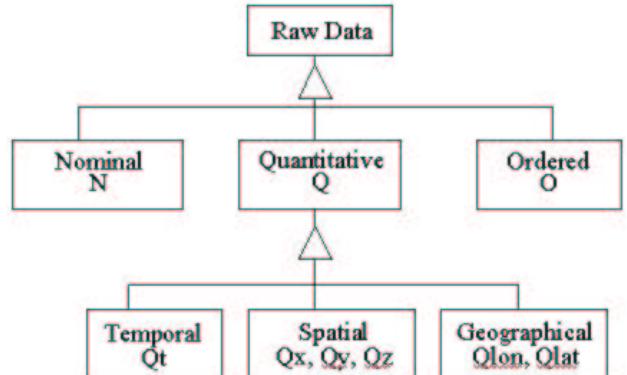


Figure 4. A UML Model of the categories of raw data. Normal abbreviations for each class are shown, for example, ‘N’ for Nominal or ‘Qlon’ for Quantitative data that is inherently longitudinal.

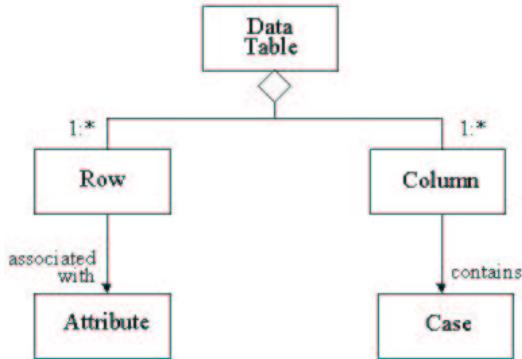


Figure 5. A UML Model of a data table. Each row of the table is associated with an attribute of the data and each column is an instance or case of data.

2.3 Visual, Auditory, Haptic Structures

Visual structures encode information by augmenting a "*spatial substrate* with *marks* and *graphical properties*" (Card, Mackinlay et al. 1999). Temporal encoding can be thought of as an animation during which the marks, their position in the spatial substrate, or, their visual properties change. A high level model of 'Visual Structure' is shown in Figure 6. Figure 7 and Figure 8 show corresponding models of auditory structures and haptic structures. Note that I have adopted the naming conventions of the visual structure model so that all three models use the basic concepts of:

- Spatial Substrate
- Marks
- Properties
- Temporal Encoding

These concepts have been proposed for visualization (Card, Mackinlay et al. 1999) but they are also applicable for both sound and touch displays. This allows us to abstract these concepts in the model of the design space. So we augment the visual, auditory and haptic *spatial substrates* with visual, auditory and haptic *marks*. These marks in turn have visual, auditory and haptic *properties*.

2.4 The Spatial Substrate

A *spatial substrate* is the most important starting point for any information display. Space is perceptually dominant and the decision about how to use space is the first design choice (Card, Mackinlay et al. 1999). The Card-Mackinlay model describes four different ways to organise space. An unstructured space has no axis. A nominal axis divides the space into regions that represent different categories. Similarly, an ordinal axis uses sub-regions but the categories have some ordering within the space. A quantitative axes uses a metric. One, two or three axis of any type may be used to describe a 1-

dimensional, 2-dimensional or 3-dimensional space. A model of the spatial substrate is shown in Figure 9.

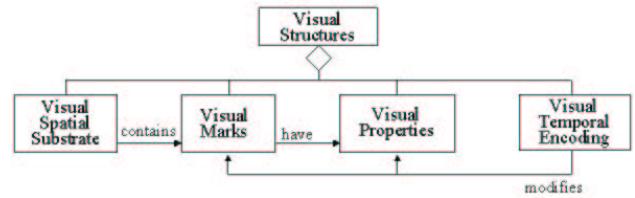


Figure 6. A UML Model of the components of 'Visual Structures'.

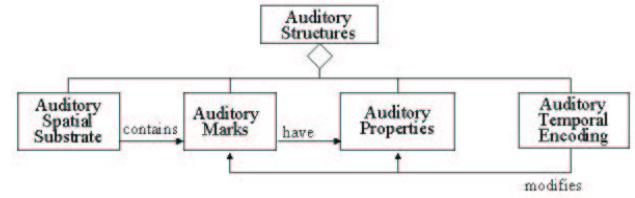


Figure 7. A UML Model of the components of auditory structures.

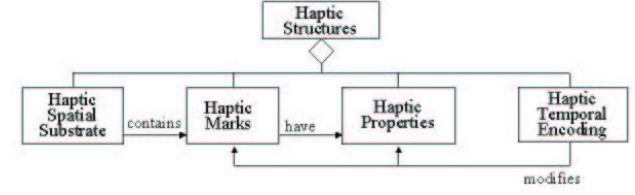


Figure 8. A UML Model of the components of haptic structures.

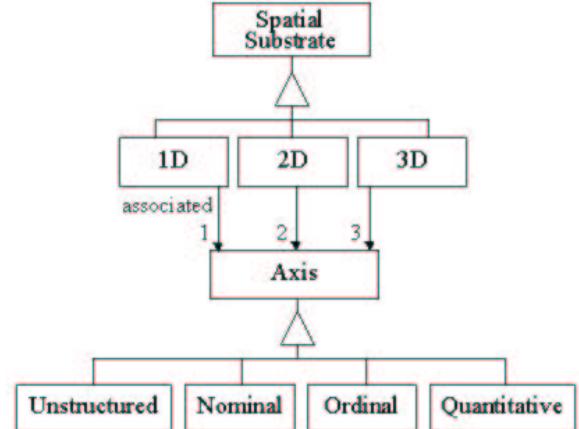


Figure 9. A UML Model of the spatial substrate.

In a multi-sensory display it would be most natural to use the same spatial substrate for each sense. If we think of the normal world, objects within space are felt and heard at the same location they are seen. It is, however, possible to consider different spaces for each sense. One useful way to use this may be to provide different resolution displays for each sense. Visual resolution is often insufficient to represent a detailed view of data without some kind of zooming. Zooming in can reveal more detailed visual

structure but the visual display must sacrifice global context. It is possible to use a much more compact auditory space within the same visual space. This allows detailed data attributes to be heard at much higher resolution while maintaining the global context with the visual display. This approach has been used for example with 'sonification' of high resolution well-log data overlaid on a much sparser visual model showing a petroleum exploration field with well locations (Fr hlich, Barrass et al. 1999).

The spatial substrate can have one, two or three dimensions. There are also a number of additional artifacts that can be contained in this substrate to assist interpretation (Figure 10, Figure 11, Figure 12). We can think of such visual landmarks as a labeled axis, grid marks or navigation aids in the space. In 3D virtual worlds it is also common to have a lighting model associated with the global space and to define the user's viewpoint in the space. However, these concepts are also applicable in the auditory space. A user may hear a 'tick' each time they pass an auditory grid mark for example. Sound can provide an excellent landmark in 3D space. The nearer the user gets to the landmark, the louder the sound becomes and the cues remain irrespective of the direction the user is facing. Globally we might also associate different acoustic models with the space. With haptics these same concepts are also possible. For example it is easy to imagine a 'haptic grid' where marks in the grid are felt as lines or bumps on a surface. Haptic navigation aids have been previously implemented where the user is 'drawn' in to buttons or 'held' by force on dial control (Hutchins and Gunn 1999). Again global haptic models can be associated with the spatial substrate. For example objects are given some weight and a gravitational field is associated with the space.

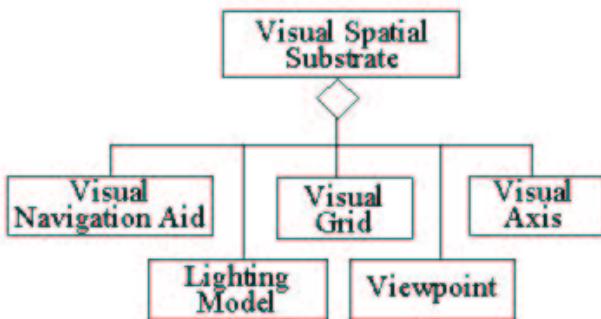


Figure 10. A UML model showing possible contents of the visual substrate.

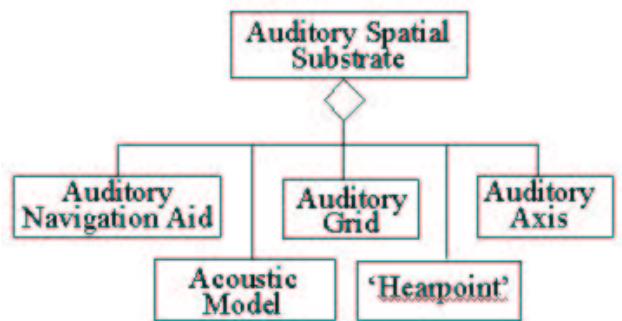


Figure 11. A UML model showing possible contents of the auditory substrate.

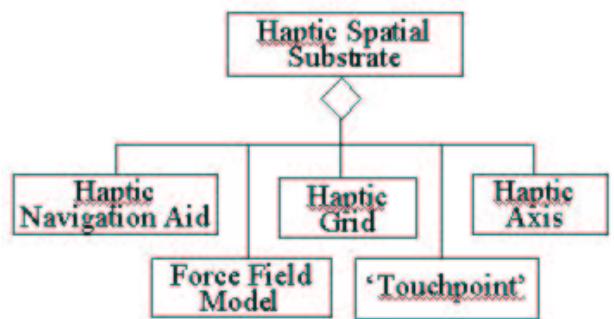


Figure 12. A UML model showing possible contents of the haptic substrate.

2.5 Marks

For visual structures, *marks* are simply elementary things that are visible in the spatial substrate (Card, Mackinlay et al. 1999). The most elementary types of marks are points(0D), lines(1D), areas(2D) and volumes(3D). The UML model of marks in Figure 13 shows these components. These elementary marks can also be used to describe elementary modeling units for both the sounds in an auditory display and the forces and tactile surfaces in a haptic display.

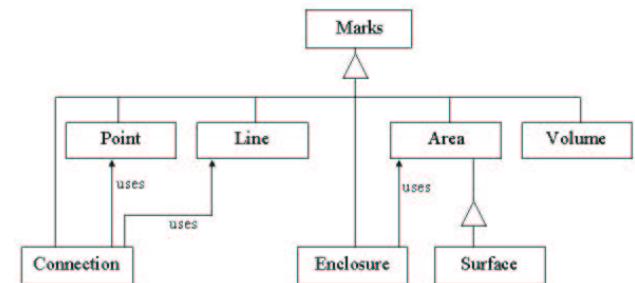


Figure 13. A UML Model of 'marks'. Note that an 'area' in 3D space is often called a 'surface'. Note also that 'Connection' and 'Enclosure' use the elementary marks to describe relationships within data.

Sound, for example, can be modeled as arising from a *point* source in space. This is our common experience in

the real world where sound originates from a source somewhere in the space. In a computer model using sound it is also possible for the user to interact with the space to generate sounds, for example, moving a cursor within a *volume*, *area* or along *lines* or *surfaces* in the space may generate auditory feedback. A simple example is where the user touches an object and sound associated with that object is heard. This can be either a surface or a volume depending on how the object is modeled. A more complex example is the modeling of fluid flow, where parameters such as flow magnitude are determined by position in the field and these parameters in turn determine the sound generated. The fluid flow field may be an *area* in a 2D model or a *volume* in a 3D model.

Haptic displays can provide both tactile and force feedback. Tactile displays provide displacements directly to the skin surface. Tactile *surfaces* are very consistent with our everyday use of touch. For example touching a surface with our fingertips and registering surface texture, slip and shape. Tactile feedback can be considered as the spatial and temporal distribution of displacements on the skin (Durlach and Mavor 1996). It is possible to model this distribution as points, lines, areas(surfaces) and volumes. Another component of the haptic sense is the kinesthetic sense which tracks position and motion of limbs and joints. Forces are sensed by the kinesthetic sensory systems and are understood as a spatial and temporal distribution of forces. Again a model of haptic marks consisting of points, lines, areas (surfaces) and volumes is appropriate. Force displays frequently use the idea of *surfaces* to model haptic objects, however, models that generate forces based on *points*, *lines* or *volumes* are also used. A gravitational field for example, may influence an *area* (2D) or *volume* (3D) of the haptic display. Again the idea of marks is useful for describing haptic structures if we think of a mark as a modeling unit that is used to generate the appropriate force or tactile feedback to the user.

2.6 Properties

The other component of visual, auditory and haptic structures that we need to consider are the properties associated with each sense. Visual, auditory and haptic properties are very different, yet there are some similarities in the organisation of our sensory perceptions that allow us to keep the models consistent. Aligned with the Card-Mackinlay model we can distinguish 'Automatic' processing from 'Controlled' processing (Card, Mackinlay et al. 1999). 'Automatic' processing involves a direct encoding of data attributes to perceptual capabilities. 'Controlled' processing requires cognitive effort to understand or interpret a more abstract encoding. A good example of controlled visual processing is text. Speech, for the auditory, and Braille, for the haptic sense, are good examples of encodings that require controlled

processing. Text, Speech and Braille all require some level of cognitive processing to decode the information.

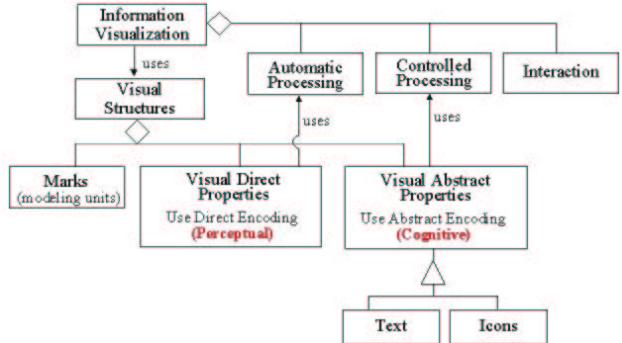


Figure 14. A UML Model of direct and abstract visual properties.

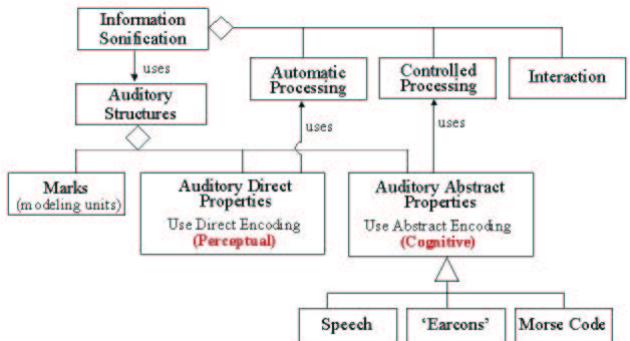


Figure 15. A UML Model of direct and abstract auditory properties. 'Earcons' are analogous to Icons used in visualizations but use a syntax that describes musical motifs (Blattner, Sumikawa et al. 1989).

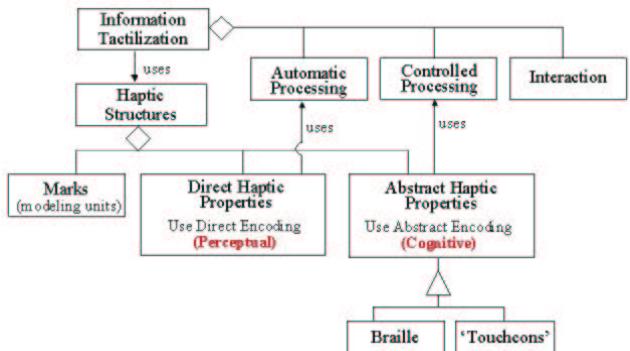


Figure 16. A UML Model of direct and abstract haptic properties. 'Touchcons' have not been described but it would be possible to use a syntax based on haptic attributes such as surface texture.

Note that I have used a slightly different terminology to that used by Card-Mackinlay. They describe abstract encodings as 'features' to distinguish them from direct encodings which are called 'properties'. I use the naming convention of 'direct properties' and 'abstract properties'. I have also used the word "Visual" where Card-Mackinlay

use the term "Graphical". The reason for these changes is to allow a more consistent naming in the UML models. High level UML models of Visual, Auditory and Haptic properties are shown in Figure 14, Figure 15 and Figure 16.

We are primarily interested in direct properties because these perceptually-direct encodings require less learning than abstract encodings and attributes of the data encoded in this way can be processed in parallel. The advantage of abstract properties is that they can express very complex concepts, and it is common for information displays to utilise them in some way, especially where detailed accurate information is required.

2.7 Visual Properties

We will now consider Visual, Auditory and Haptic properties individually. Of the three 'Visual properties' have been the most frequently studied and applied. Bertin (Bertin 1999) for example described six basic properties of size, orientation, gray scale, color, texture and shape and Mackinlay (Mackinlay 1986) used a rule-based system for directly mapping from data attributes rules to properties. A number of other properties have also been suggested that allow for automatic processing. These include, length, line orientation, width, curvature, intensity and 3d depth cues (Figure 17) (Card, Mackinlay et al. 1999).

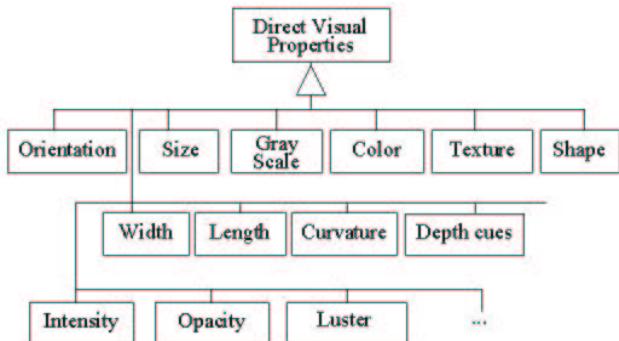


Figure 17. A UML Model of direct visual properties.

2.8 Auditory Properties

Two different types of listening have been distinguished, *Everyday listening* and *Musical listening* (Gaver 1986). *Everyday listening* focuses on attributes of the sounds source. In the real world these attributes can reveal a lot of information. For example, when a object is tapped a number of questions are asked. What material is the object made of? Is the object hollow, does it contain anything? How hard was the object struck? Thus properties or attributes of the object are revealed by interpreting the sound. When displaying abstract data everyday sounds are useful for displaying categorical data by using a cross-section of sounds as signatures of categorical data.

Musical Listening involves the skills used to appreciate music. Musical listening helps to discriminate pitch and timbre. It also helps discern a number of temporal patterns such as rhythm and melody. The ability to hear information in music varies greatly between individuals. Figure 18 shows the 'Direct Auditory Properties'. Note that our sense of hearing is very proficient at monitoring and so understanding information that evolves over time. Hence temporal encodings are most important for interpreting both everyday and musical sounds.

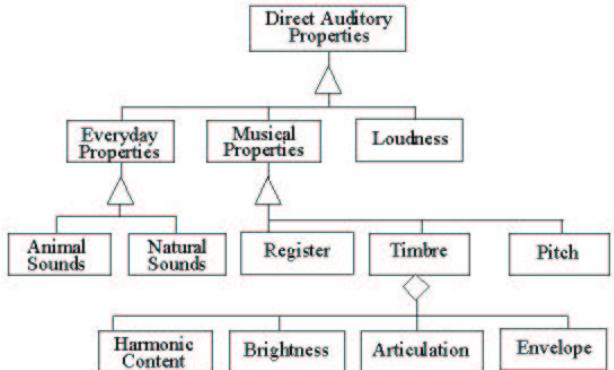


Figure 18. A UML Model of types of sound.

2.9 Haptic Properties

Tasks performed by the sense of touch can be divided into either "exploration" or "manipulation" tasks (Durlach and Mavor 1996). Since we are most interested in display of properties we are more interested in the exploration tasks which are sensory dominant. However, despite the division into sensory and manipulation, most haptic tasks involve some combination of exploring and manipulating (Figure 19).

There are many types of information gathered by the different sensory receptors. While this information includes temperature, pain, tactile, chemogenic and kinesthetic information (Figure 20) it is only tactile and kinesthetic information that can currently be displayed by existing user interface devices. Tactile refers to the sense of contact with an object, while kinesthetic refers to the sense of motion and position in space of joints and limbs (Figure 21).

The direct tactile properties are shown in Figure 22 and the direct kinesthetic properties are shown in Figure 23. The sense of touch is like hearing in that information is often conveyed by how the properties evolve over time. Hence temporal encodings for haptics must be considered carefully.

Haptic displays developed for use in telemanipulation and only in relatively recent times have they been integrated more generally as a component of the user interface. The Phantom from Sensable (Salsbury and Srinivasan 1997) technologies is a force feedback device. It is the most

generally available and practical devices for displaying haptic properties. However, it allows only forces to be displayed at a point which limits the display of tactile properties and prevents the simultaneous display of forces over a space greater than a single point. Despite this it is still possible to display many direct properties.

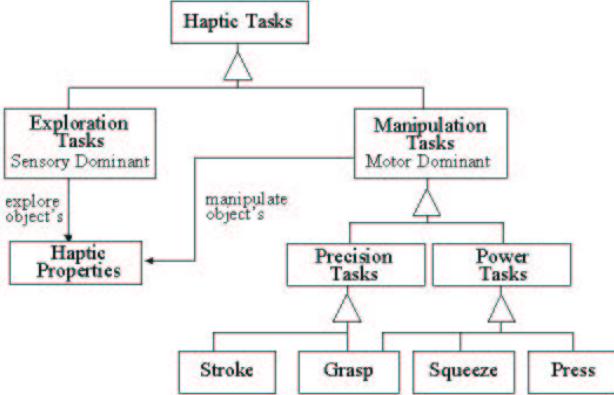


Figure 19. A UML Model of the two main types of haptic tasks, exploration and manipulation. For most tasks our haptic sense both senses and acts on the environment.

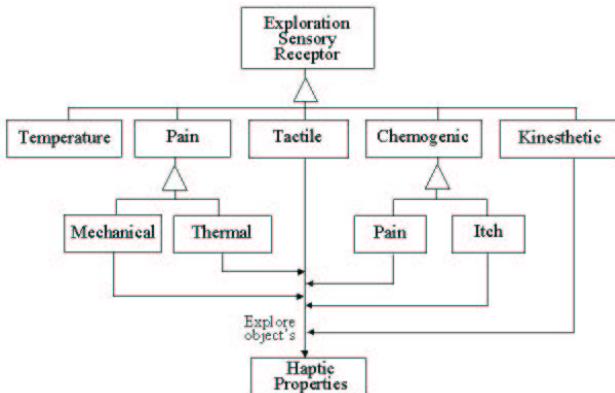


Figure 20. A UML Model of types of the types of haptic sensory receptors.

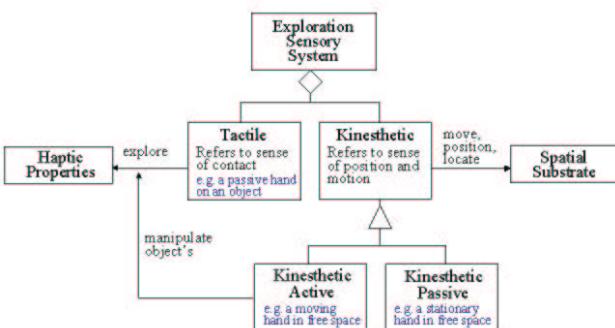


Figure 21. A UML Model of the tactile and kinesthetic senses. Currently it is not practical to provide output to the other haptic components of

pain, heat, itch.

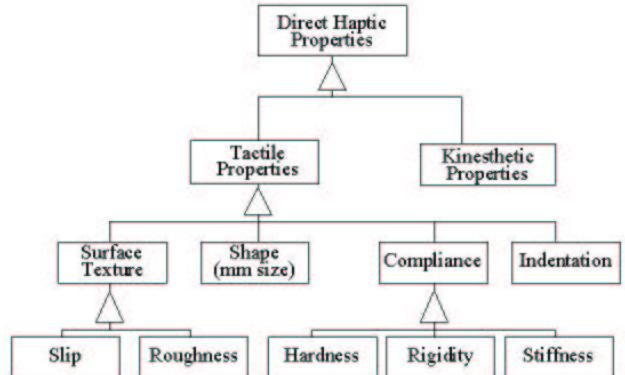


Figure 22. A UML Model of direct haptic properties, showing tactile properties.

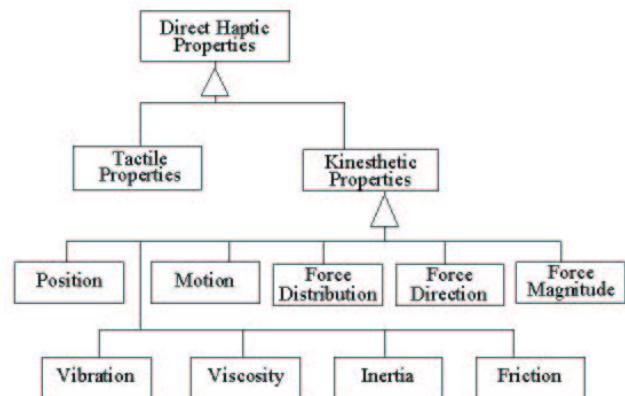


Figure 23. A UML Model of direct haptic properties, showing kinesthetic properties.

2.10 Temporal Encoding

The final part considered are temporal encodings for each sense. Temporal encodings modify the position of marks or their properties over time (Figure 6, 7, 8). Visual temporal encodings are relatively straightforward and are useful for studying data which changes over time. This can be reflected by a movement of the marks or change to some property like colour (Figure 24). Auditory temporal encodings are very important as the variation in sound properties over time conveys detailed information and complex properties in the data can be understood as musical qualities such as rhythm, melody (Figure 25). It is also possible to design haptic temporal encodings, for example where the hardness of an object changes (Figure 26).

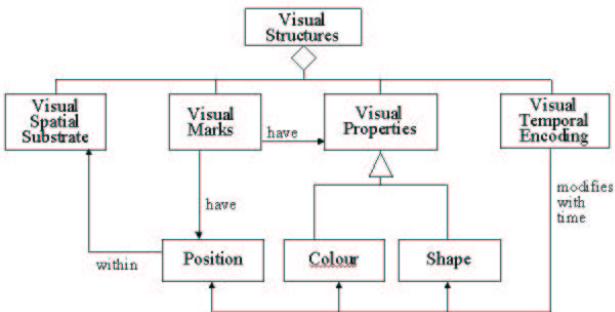


Figure 24. Visual Temporal encoding.

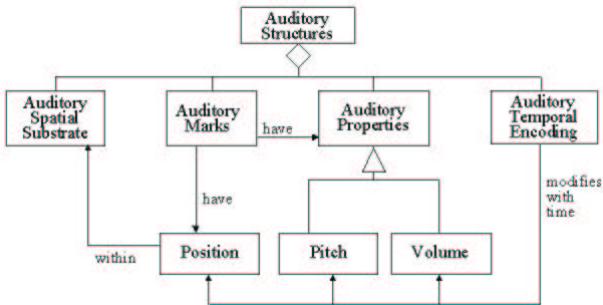


Figure 25. Auditory Temporal Encoding

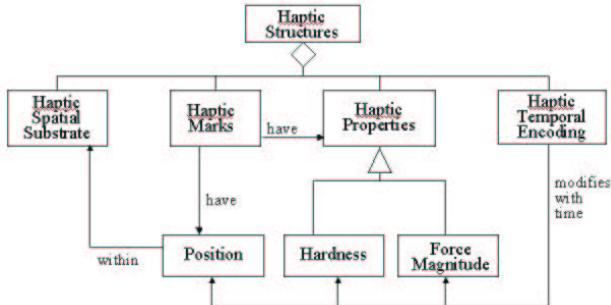


Figure 26. Haptic Temporal Encoding

3 The Metaphor Model of the Design Space

The previous discussion has focused on the extension of a design space that was originally proposed by Card-Mackinlay (Card, Mackinlay et al. 1999) for information visualisation. A previous classification of the same multi-sensory design space based on metaphors has also been proposed (Nesbitt 2000).

Metaphors provide a starting model that the user may take advantage of to help understand structure or relations in the visualisation. Metaphors are often used as a starting point in designing information displays. Metaphors not only allow the user to take advantage of existing cognitive models but they also take advantage of ecologically-developed perceptual skills. There are many difficulties in designing a multi-sensory display as perceptual conflicts occur. Using metaphors from the real world as models for the design of displays can make sure

that we utilise our perceptions in the information world as we do in the real world.

The metaphor classification describes 5 broad clusters of metaphors (Table 1) which are discussed below. The first two clusters contain spatial and temporal metaphors that are applicable to all senses. The other three clusters are metaphors from sight, sound and force specific to the visual, auditory and haptic sense.

Metaphor Cluster				
Spatial	Temporal 1	Sight	Sound	Touch

Table 1. Classification of metaphors

1. ‘Spatial Metaphors’ relate to scale, location and structure. Spatial metaphors can carry quantitative information. Relationships can be described by position on a map or a two or three-dimensional grid. Data placed in proximity can be visually assessed in compare and contrast activities. Structures such as tree graphs or data maps can carry broader overview information that is important to the user. Both touch and sound also provide useful cues for object position in space. Spatial metaphors are appropriate for all senses and concern the way pictures, sounds and forces are organised in space.
2. ‘Temporal Metaphors’ are concerned with how data changes with time. It includes concepts of movement, animation, rhythms and cycles. Interaction in a virtual environment, as in the real world, presents information that can change with time. These changes can carry information. Temporal metaphors will also be applied to all senses and concern how we perceive changes to pictures, sounds and forces over time.
3. ‘Sight Metaphors’ use direct mappings from information to the attributes of sight. These include colour, light, shape, and surface texture (Hutchins and Gunn 1999). The use of a colour scale is an example of a common mapping used to represent data values (Nesbitt 2000). Icons are an example of how abstract shapes can be used to convey information using intuitive symbols.
4. ‘Sound Metaphors’ deal with direct mappings of typical sound properties such as pitch, amplitude, timbre and also more musical qualities such as rhythm and

melody. Auditory metaphors are less common, however good examples exist in the real world. The Geiger counter uses sound to display radiation levels and is a well understood auditory metaphor (Salsbury and Srinivasan 1997).

5. 'Touch Metaphors' relate to tactile properties such as force, inertia and vibration. It is possible to assess object properties such as weight and density by the inertia that needs to be overcome when moving an object. Other object properties such as the hardness and surface texture can also be used to encode information.

Altogether there are nine broad categories of metaphor which make up this classification. They are:

1. Visual Spatial Metaphors
2. Visual Temporal Metaphors
3. Sight Metaphors
4. Auditory Spatial Metaphors
5. Auditory Temporal Metaphors
6. Sound Metaphors
7. Haptic Spatial Metaphors
8. Haptic Temporal Metaphors
9. Touch Metaphors

Sense	Card-Mackinlay	Metaphor
	Visual spatial substrate augmented with visual marks	Visual Spatial Metaphors
	Visual temporal encoding	Visual Temporal Metaphors
	Direct visual properties	Sight Metaphors
	Auditory spatial substrate augmented with auditory marks	Auditory Spatial Metaphors
	Auditory temporal encoding	Auditory Temporal Metaphors
	Direct auditory properties	Sound Metaphors
	Haptic spatial substrate augmented with auditory marks	Haptic Spatial Metaphors
	Haptic temporal encoding	Haptic Temporal Metaphors
	Direct haptic properties	Touch Metaphors

Table 2. Correlation between the metaphor design space and the extended Card-Mackinlay design space.

The correlation between the metaphor design space and the Card-Mackinlay multi-sensory design space is shown in Table 2. There is a natural correlation between temporal metaphors and the concept of temporal encodings. Similarly the idea of a spatial substrate with marks matches to the idea of spatial metaphors. Finally the sight, sound and touch metaphors correspond to the direct properties for each sense.

4 Conclusion

I have outlined two architectures of classification for multi-sensory design space. One is based on an extension of the previously proposed classification of Card-Mackinlay. The other classification is a previously proposed metaphor classification. The two classification are shown to cover the same design space.

During the next stage of work guidelines are being developed to assist in understanding how to apply different parts of the design space for different tasks. This will be tested in different application domains.

More work also needs to be done in verifying the correctness of the architecture especially in the less well understood domains of sound and haptics.

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