Variables for Data Physicalization Units

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Abstract—We propose a set of variables for unit-based data physicalisation. Variables are symbolic properties that can be applied to data in order to represent information. Unit based data physicalizations are physical representations of data made out of multiple pieces (units), with each units corresponding to a data point. We propose 14 variables grouped in four categories, but focus on nine that are novel and most relevant for data physicalizations: geometric variables (position, orientation, *global shape*, *exact shape*), color variables (hue, saturation, luminance, *optics*), tactile variables (*roughness*, *lay*, *temperature*, *compliance*), and kinesthetic variables (*slipperiness*, *weight*). This set of variables offers a better grasp of the design space, and provides building blocks for the systematic construction of data physicalizations.

Index Terms—Physicalization, unit, constructive, visualization, perception, variables.

1 Introduction

The spectrum of data physicalizations is very wide, ranging from interpretive data sculptures, to extremely precise and legible physical data models. Many physicalisations are still done on a one-off basis, and adapting the principles from one data-set or representation to another is rarely straightforward. The emergence, or resurgence, of data physicalisations raises a number of questions ranging from human perception [1], to design methods [2], to engineering problems [3].

We propose a set of variables to support the systematic design and fabrication of physicalizations. In order to produce a meaningful characterization, we focus on a subset of physicalization that can be incrementally composed.

2 Unit based Data Physicalization

Unit-based data physicalisations are physical representations of data composed of pieces (units), with each unit corresponding to a data point. Taking a modular approach presents several benefits: from a design point of view, units can be parametrized and produced quickly with rapid fabrication methods, e.g. laser cutting or 3D printing. Modular pieces can be assembled in a systematic manner, rather than in an ad-hoc fashion. Modularity enables data physicalisations to be "updated" as new data units are generated. Finally, and while this has to be confirmed experimentally, structuring the physicalisation around units, probably improves users' parsing and interpretation of the data.

The unit based physicalizations presented here are discussed in Stusak's dissertation [4], and relate to the work on constructive visualization [5], [6] and unit-based visualization [7]. Huron et al. make the analogy between tokens and Bertin's *marks* in information visualization [6]. However, this analogy is difficult to maintain in a completely physical context. In physicalization, the tokens are generally 3-dimensional shapes. And shapes do not fit properly in the classical distinction between marks and channels [8] (chapter 5, page 96). Shapes are multidimensional and can encode information alongside different axes.

Multiple channels can be used to encode attributes on a physical unit. Figure 1 shows a unit representing information about a run: duration, distance and average speed. In this example, the global shape (defined by the diameter) encodes the duration of a run.

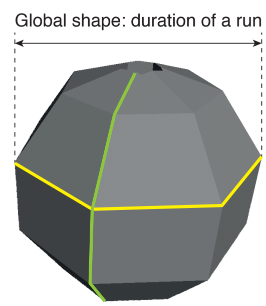

Fig. 1. Unit example from the Activity Sculpture [9] project, the bead represents the information about one run (distance, speed, and duration).

We propose a set of variables for unit-based data physicalisation. These variables describe how the units can be modified, by varying their size, shape, color, etc. Unlike traditional infovis the variables are not only visual but also aimed at other senses like tactile or kinesthetic senses.

2.1 Limitations

The variables discussed here are a preliminary proposal, and experiments are required to understand how units are perceived individually, but also when combined. We only consider the design and perception of physicalization in *normal conditions*, as Bertin does in his semiology of graphics [10] (can be fabricated with existing techniques, visible at a glance, reading distance of a book, normal and constant lighting). In line with Gibson's work on perception, we only consider *"substantial surfaces"*, i.e. we ignore liquids and gases. We do not take into account and do not intend to characterize the role actuation could play in the design

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and perception of physicalization. Finally, when discussing the efficiency of the variables we are focusing on sensing capabilities that fit within human norms.

3 Description of Variables

We propose 14 variables, but will focus on the 9 that we consider novel and most relevant for data physicalizations. We classified them into the following four categories: geometric variables (position, orientation, *global shape*, *exact shape*), color variables (hue, saturation, luminance, *optics*), tactile variables (*roughness*, *lay*, *temperature*, *compliance*), and kinesthetic variables (*slipperiness*, *weight*).

We limited the number of variables by focusing on properties that are studied in the area of haptic perception and that can be fabricated with state-of-the-art digital fabrication technologies, or are part of active research in the area of infovis or HCI. We ignored properties that seemed less appropriate for encoding data in unit-based physicalizations or required actuation. Throughout the presentation of the variables, we use the beads from the *Activity Sculpture* project (see Figure 1) as an example to illustrate how the variables could be applied.

3.1 Geometric Variables

Geometric variables consist of four variables, going from the macro- to the micro-level. As position and orientation are intensively discussed in previous articles about visual variables, we will focus on *global shape* and *exact shape*. The *global shape* can be described as the bounding box of a unit, the *exact shape* can be seen as the contour of it. Although *roughness* and *lay* could be classified as a micro-level of the *exact shape*, we categorized them as *tactile variables* since they are directly related to touch.

3.1.1 Position and Orientation

The position and orientation of single physical units are similar to classical visualization variables. Since physicalizations are part of the physical world their positions can be defined in three variables: x, y, and z. However, physicalizations are also subject to gravity which hinders the free positioning of units in 3D space. While it is out of the scope for this article, the kinesthetic location, i.e., the location of the unit in relation to the body and its reachability, i.e., in an arm's length distance, are aspects worth considering for physicalizations.

In the case of the bead presented above, its position can be defined on a linear axis (before/after other beads) and its orientation is aligned along its z axis.

3.1.2 Global Shape

With *global shape* we mean the global dimension of a unit. This variable is similar to the visual variable size, which is based on the length, area or volume of a mark. It can also be described as a coarse bounding box for a unit, in order to highlight the focus on the global appearance and to exclude finer details of shapes.

The global shape of the bead would be the size or volume of a surrounding sphere and therefore, ignoring the exact shape, defined by the width and height segments. The global shape can be perceived with the visual and haptic senses. However, we believe the visual sense plays a stronger perceptual role, while the haptic sense may be more suited to local features, such as the exact shape or the surface.

3.1.3 Exact Shape

The *exact shape* of a unit is its actual contour or its outline. We also see the surface finish term *waviness* as part of the *exact shape*. In InfoVis, definitions vary on whether shape is based on simple geometry, or also includes icon, symbols or compound glyphs [8]. Furthermore, there is a long list of visual attributes associated with shape, such as closure, hole, curvature, or line ending (see [11], [12] for a more detailed description). We focus our initial categorization of physical variables on well-known 3D modeling techniques, such as constructive solid geometry and polygon mesh to describe and define the exact shape of a unit.

The exact shape of the bead is defined by the number of width and height segments. The global and exact shape influence each other. When the width or height of segments change for example, the volume of the bead alos changes. They also can be equal, e.g., if the unit is a primitive, such as a sphere or a cuboid. The exact shape can be perceived with both the visual and haptic sense. While the visual sense is primarily used to perceive the exact shape, the haptic sense can support the perception of small shape changes.

3.2 Color Variables

We identified four color variables, three of them are already discussed in previous work. We add to these three well-known color variables the *optics* variable, which focuses on physical properties of materials and objects, that influence the behavior of light.

3.2.1 Hue, Saturation and Luminance

The color variables hue, saturation and luminance have the same characteristics as in digital visualizations. Other sources such as Bertin [10], Carpendale [13] or Munzner [8], already discuss these color variables at great length.

3.2.2 Optics (Transparency and Reflection)

Under the umbrella term *optics* we refer to the branch of physics which involves the behavior and properties of light. While the whole surface of paper sheets or screens behave optically in the same way generally. For 3D physicalizations, the material properties of single units can have differently optical properties. These properties are only perceivable through the visual sense.

Transparency and reflection are the optical properties most relevant to physicalizations. We grouped them under optics, because they both have an impact on absorption, scattering, and refraction, which are what the eye will perceive.

Each bead could have a different level of transparency or reflection. It is worth mentioning that these properties are highly dependent on the environment and the position of the observer. Without any light source reflections are rather not perceivable. It can also be necessary for the observer to move her head or the entire body to perceive and notice possible differences in these properties.

3.3 Tactile Variables

We classified *roughness*, *lay*, *coldness* and *compliance* as the most relevant variables in the tactile category. Cutaneous cues seem to be the most important ones for tacticle variables. We already included *Waviness* in the *exact shape* category, although it describes a surface texture.

3.3.1 Roughness

Roughness is a component of a surface texture which received most attention within haptics research. When a surface has irregularities or ridges, it can be described as rough. The *roughness* variable is related to the visual variable texture or grain (see [10], [13]). However, we will focus here on the physical surface, i.e., textures that are also perceivable with the haptic sense and not only visual.

It could be possible to provide each segment of the bead or each bead itself with a different level of roughness according to the underlying data. While the roughness of a surface in some cases can be perceived visually, e.g., different grits of sandpaper, the haptic sense is necessary and allows a finer perception.

3.3.2 Lay

In manufacturing *lay* defines the direction of the predominant surface pattern [14]. Lay relates to the visual variables of orientation and texture, but also to *roughness* and *exact shape*. *Lay* can have one linear direction, e.g., parallel or perpendicular to the observer. It can also have two or more crossed directions, be circular or radial relative to a center point on the surface, or even completely scattered. To our knowledge, there are no studies specifying how many different directions are perceivable by humans and under which circumstances.

Similarly to *roughness*, different *lay* patterns could be used for various segments of a bead or for each bead. While lay patterns can be perceived visually, the haptic sense allows a more detailed perception.

3.3.3 Coldness

We focus here on *perceived coldness* of an object at room temperature (since we do not consider actuation). This is distinct from the object's temperature, which is independent from the material. Different materials have different cooling curves, which define the perceived coldness. It is related to the heat extraction from the fingers when touching a material. As a consequence, the perceived coldness is influenced by the manner of touching and the contact resistance between the finger(s) and the object. While coldness can only be perceived with the haptic sense, the visual sense could influence the expected coldness based on previous experiences, e.g., metal is perceived colder than plastic.

As an example, each bead could have a different cooling curve depending on the materials used, and feel different on touch.

3.3.4 Compliance

Compliance can be expressed physically in various ways and has a number of different characteristics, e.g., malleability, elasticity or plasticity. We focus on the perceived *compliance* which can be described as softness or hardness of a material. While compliance perception does not depend on kinaesthetic force information, it can be influenced by it. Studies showed a strong relationship between perceived hardness and physical stiffness [15].

In the example of the beads, each bead or even specific parts of it could have different levels of compliance. While the visual sense could influence the expectancy, e.g., metal is harder than plastic, different version of plastic can have different levels of *compliance*, which can be perceived only with the haptic sense. Stiffness also depends on the object's dimension as a thick, narrow object can be compressed more than a thin, wide object made of the same material, using the same force.

3.4 Kinesthetic Variables

We classified as *kinesthetic variables* the variables *slipperiness* and *weight*. Both depend on the combination of cutaneous and kinaesthetic cues for an accurate perception.

3.4.1 Slipperiness

As *slipperiness* we describe the friction that occurs when one surface, e.g., a finger, slides over another. Movement is essential for an accurate perception of slipperiness. While slipperiness and roughness are quite distinct from a physical point of view, there may be some overlap perceptually and linguistically [16].

Again, each bead could have an different level of slipperiness. While people can feel clear differences in resistance for different materials when they move their finger over the surface, there is little research about the relationship between the perceived intensity and the physical intensity. Slipperiness can only be perceived by the haptic sense and depends on humidity, but also force and speed of movement.

3.4.2 Weight

The perceived weight depends on a wide variety of mechanisms, such as prior experience, volume or thermal properties. Weight can only be perceived through the haptic sense, by lifting or at least moving it.

In the example of the beads each bead could have a different weight. It is important to mention that the weight of a unit can only be perceived when it is detached. In contrast to variables such as roughness or slipperiness the perception of weight will change when multiple units are combined, i.e., the object will get heavier.

4 Performance of Variables

We discuss the performance of variables along four characteristics introduced by Bertin for visual variables [10] (Table 1). We believe these characteristics are not only applicable for visual variables but also for physical variables. They help to understand how a change in a specific variable can affect the perception and therefore, the performance of a particular task (see also [13]):

- *Selective:* A variable is selective if a change in this variable alone makes it easier to select that changed unit from all other units.

- *Associative:* A variable is associative if a unit can be grouped according to this variable alone as they differ in other variables.
- *Quantitative:* A variable is quantitative if the relationship between two units can be obtainable as a numerical difference of this variable.
- *Order:* A variable is ordered if changes in this variable support a ordered readings of the units.

Haptic stimuli must be processed more linearly than visual ones. Therefore, the ranking relies on the possibility that these sensing tasks can be accomplished in a short time frame of a few seconds. This differs from Bertin's approach which only considered perception of whole visualizations and did not consider sequential inspection as supporting selective or associative performances.

The difference between "possible" and "good" is based on our experience with physicalizations, and research in the haptic domain. Like Bertin, we present the assumed performance based on a systematic inspection of the variables (i.e. not on experimental work). These assumptions should be refined and (in)validated through experimental research to properly characterize the performance of each variable, and the combination of variables. We discuss below the performance of variables that are less explored in infovis research (gray lines in the table).

TABLE 1
Performance of variables ("good" ✓; "possible" ∼; "not possible" ×)

Variables	Selective	Associative	Quantitative	Order
Geometric Variables				
Position	✓	✓	✓	✓
Orientation	✓	✓	×	∼
Global Shape	✓	✓	∼	✓
Exact Shape	✓	✓	×	∼
Color Variables				
Hue	✓	✓	×	×
Saturation	✓	✓	×	✓
Luminance	✓	✓	×	✓
Optics	✓	✓	×	✓
Tactile Variables				
Roughness	✓	✓	×	✓
Lay	✓	✓	×	∼
Coldness	✓	✓	×	✓
Compliance	✓	✓	×	✓
Kinesthetic Variables				
Slipperiness	✓	✓	×	✓
Weight	✓	✓	×	✓

4.1 Geometric Variables

Global shape and *exact shape* are both *selective* and *associative*, as a unit that has changed this characteristic alone, will become distinct and selectable from the other units, but can also be used to create groups. However, for the *exact shape* it depends on the number of units displayed, the actual shapes and how strongly the various shapes differ.

Changes of the *global shape*, e.g., the volume, are difficult for comparative numerical interpretations. However, if the change is based on a repetition of the same unit a numerical reading could be possible and therefore can be *quantitative*. Changes in the *exact shape* can hardly provide any numerical interpretation, therefore it is not *quantitative*. While it could be argued that the number of height and width segments of the bead from the Activity Sculpture project (see Figure 1) could be used for a numerical difference, we do not believe that this is suitable.

Changes in the *global shape* are easily orderable, but this is not the case for *exact shape*. A shape does not support an ordered reading or the criteria would be of personal preference. However, the bead from the Activity Sculpture project (see Figure 1) changes its shape from angular (few segments) to smooth and round (more segments). Such changes in the exact shape could be ordered, but it would require some learning.

4.2 Color Variables

Optics is similar to the well-know visual variables saturation or luminance. A unit that has changed its level of transparency or reflection alone will become distinct and units with the same level can be interpreted as belonging together. The relationship between different levels of transparency or reflection cannot be seen as numerical. For example, one unit will not be perceived as four time as transparent as another one. Both, transparency and reflection support ordered readings, as, for example, one unit can be perceived as more transparent or reflective than another one.

4.3 Tactile Variables

All tactile variables can be seen as *selective* and *associative*. A unit that changes one of these dimensions will become selectable from the other units, but can also serve to create groups of units. Under specific conditions, *Roughness* and *coldness* can support a haptic pop-out effect [17], [18].

None of the dimensions can be seen as *quantitative*. Although it is possible to measure, the *roughness* or *coldness* of a surface, humans are not able to perceive those characteristics accurately, especially that one object is two times as warm or rough as another one [16].

All dimensions beside *lay* can be seen as *orderable*. One unit can be rougher, colder or harder than another one. *Lay* is similar to the visual variable *orientation*. There can be a notion of order if the changes are progressive, e.g., only the direction of the pattern changes clockwise. However, establishing an order between a circular and a linear pattern is not possible.

4.4 Kinesthetic Variables

Both *slipperiness* and *weight* are *selective* and *associative*, as a unit with a different weight or level of friction will become distinct and selectable. Units with the same weight or level of friction can be interpreted as belonging together.

Although the *slipperiness* and *weight* be expressed physically, both dimension are not *quantitative*, as a unit can hardly be perceived as twice as heavy as another one. But both can be ordered, as a unit can be heavier or can have a higher level of friction than another one [19].

5 Conclusion

We proposed a set of variables to describe unit-based physicalizations, and discussed their performance. We excluded the characteristic of length, which describes how many distinct values a variable can support, and thereby how much information it can convey. We did not discuss how variables can be mixed and how this would be perceived, which is relevant to any real-life scenario. We also focused mostly on the visual and haptic senses, but other senses such as sound or taste should also be considered.

We hope that this paper serves as a prompt to explore in a more systematic manner the physical variables we proposed, and our assumptions on perception performance. Jansen and Hornbaek paper on the perception of size as a physical variable [1] is an excellent example of such studies. It should be replicated and extended to other variables.

Finally, the constructive or unit based approach offers serveral benefits in terms of design, fabrication, and perception. But this should not disminish our attention to higher level cognitive aspects, such as how people explore and understand the data. This is especially relevant given how the haptic sense requires more sequential exploration compared to sight. Moreover memory aspects, learning processes or support for social interaction should also be considered to further our understanding of unit-based physicalization.

References

[1] Y. Jansen and K. Hornbaek, "A psychophysical investigation of size as a physical variable," *IEEE Transactions on Visualization and Computer Graphics*, vol. 22, no. 1, pp. 479–488, Jan 2016.

[2] T. Hogan, E. Hornecker, S. Stusak, Y. Jansen, J. Alexander, A. V. Moere, U. Hinrichs, and K. Nolan, "Tangible data, explorations in data physicalization," in *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 2016, pp. 753–756.

[3] S. Swaminathan, C. Shi, Y. Jansen, P. Dragicevic, L. A. Oehlberg, and J.-D. Fekete, "Supporting the design and fabrication of physical visualizations," in *CHI '14*. New York, NY, USA: ACM, 2014, pp. 3845–3854.

[4] S. Stusak, "Exploring the potential of physical visualizations," Ph.D. dissertation, Ludwig-Maximilians-Universität München, August 2016.

[5] S. Huron, Y. Jansen, and S. Carpendale, "Constructing visual representations: Investigating the use of tangible tokens," *IEEE Transactions on Visualization and Computer Graphics*, vol. 20, no. 12, pp. 2102–2111, 2014.

[6] S. Huron, S. Carpendale, A. Thudt, A. Tang, and M. Mauerer, "Constructive visualization," in *Proceedings of the 2014 Conference on Designing Interactive Systems*. New York, NY, USA: ACM, 2014, pp. 433–442.

[7] D. Park, S. M. Drucker, R. Fernandez, and N. Elmqvist, "Atom: A grammar for unit visualizations," *IEEE Transactions on Visualization & Computer Graphics*, no. 1, pp. 1–1, 2018.

[8] T. Munzner, *Visualization Analysis and Design*. CRC Press, 2014.

[9] S. Stusak, A. Tabard, F. Sauka, R. A. Khot, and A. Butz, "Activity sculptures: Exploring the impact of physical visualizations on running activity," *IEEE Transactions on Visualization and Computer Graphics*, vol. 20, no. 12, pp. 2201–2210, 2014.

[10] J. Bertin, *Semiology of graphics: diagrams, networks, maps*. University of Wisconsin press, 1983.

[11] R. Brath, "Multiple shape attributes in information visualization: Guidance from prior art and experiments," *18th International Conference on Information Visualisation*, vol. 0, pp. 433–438, 2010.

[12] R. Brath, *Information Visualisation: Techniques, Usability and Evaluation*. Cambridge Scholars Publishing, 2014, ch The multiple visual attributes of shape, pp. 43–66.

[13] S. Carpendale, "Considering visual variables as a basis for information visualisation," in *Technical Report #2001-693-16*. University of Calgary, 2003.

[14] E. De Garmo, J. Black, and R. Kohser, *DeGarmo's Materials and Processes in Manufacturing*. Wiley, 2011.

[15] S. Lederman and R. Klatzky, "Human haptics," *LR Squire (Ed. in Chief), Encyclopedia of neuroscience*, vol. 5, pp. 11–18, 2009.

[16] W. M. B. Tiest, "Tactual perception of material properties," *Vision Research*, vol. 50, no. 24, pp. 2775 – 2782, 2010, perception and Action: Part I.

[17] M. A. Plaisier, W. M. B. Tiest, and A. M. Kappers, "Haptic pop-out in a hand sweep," *Acta Psychologica*, vol. 128, no. 2, pp. 368 – 377, 2008.

[18] M. Plaisier and A. Kappers, "Cold objects pop out!" in *Haptics: Generating and Perceiving Tangible Sensations*, ser. Lecture Notes in Computer Science, A. Kappers, J. van Erp, W. Bergmann Tiest, and F. van der Helm, Eds. Springer Berlin Heidelberg, 2010, vol. 6192, pp. 219–224.

[19] S. J. Lederman and R. L. Klatzky, "Haptic perception: A tutorial," *Attention, Perception, & Psychophysics*, vol. 71, no. 7, pp. 1439–1459, 2009.