Play with data: Using haptic properties of artifacts to augment data representation

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This article explores the potential of haptic data representation, especially for everyday data requiring scrutiny such as accident reports and behavior habits. Although haptic properties of artifacts have been used to portray data, the data types represented by haptic properties are primarily confined to frequency and average value. Crucial information, such as variance, trend, and sample size, remains underutilized, despite their significance in decision making and reflection. To address this, we conducted a user study to investigate people's mental mappings of haptic properties to various aspects of data. The results suggest a common pattern of people's preferences for interpreting haptic properties, revealing specific mappings between haptic properties and data types. Following this, a design workshop demonstrated the feasibility and benefits of holistically representing multiple data types using haptic properties. This integrated approach has the potential to enhance the depth and breadth of data interpretation.

Keywords: empirical studies; haptic; haptic properties; mappings

1 Introduction

Physical data representation differs from what you see on a screen because you can touch it and feel its physical properties. Physical artifacts allow us directly handle and play with data when examining and evaluating design outcomes (Hull & Willett, 2017), making the represented data easier to remember (Stusak et al., 2015), and eliciting greater empathy for data (Cheok et al., 2008). The haptic data representation is applicable to a wide range of data types (van Koningsbruggen et al., 2022), and can integrates with other techniques such as augmented reality to create an explorative visualization experience (Herman et al., 2021).

This article attempts to use the strengths of haptic properties to apply physical data representation in daily lives. Researchers have developed ways to represent data using these touchable qualities (Dobson et al., 2001; Nakagaki et al., 2019). Houben et al. (2016), for instance, used physical cubes to remind air conditions. However, the data types that researchers explored appear to be constrained, the majority of applications so far were related to the frequency and average value of activities and events (Lee et al., 2015; Wun et al., 2016). There are many other valuable aspects of data, such as variance, gradient, and sample size (Roberts & Franklin, 2005). These properties are vital because they provide a complete picture and guide our actions and thoughts. We make decisions based not only on average values, but also on trends and expectations. For example, when buying stocks or moving to a new city, the price changes and the fluctuation of temperature matter more than the average value. The sample size and gradient also act as important references when reading reports on accidents and diseases.

Given that people can experience multiple haptic properties at once when handling a physical object, a holistic impression about the data can be created by employing these properties to convey different aspects of data. Allowing people to grasp and play with data artifacts fosters human-data connection and creates emotional engagement. Additionally, this might increase people's awareness of data. For example, people could grab an artifact representing running data and reflect their running activities. Another example could be comparing accidents in two regions. A big, heavy and vibrating artifact could create a perception of a larger number of accidents and more vibrant conditions than a small, light and static artifact. To achieve this holistic impression of data, we need to find a natural link between haptic properties and data attributes. However, it is uncertain whether people have similar mental mappings between haptic properties of artifacts and data attributes, or whether these mappings affect how well people understand and use the data.

This article explores the possibilities of data presentation using multiple haptic properties. The initial focus was on data properties related to individual variables such as variance and sample size. A user study was carried out to investigate people's mental mappings between haptic properties and data types, as well as their task performance using these properties. This helped figure out how to encode data with appropriate haptic properties. On the basis of the study's findings, a design workshop was conducted and several artifacts were designed to demonstrate the potentials of employing multiple haptic properties to represent data in daily lives. The study contribute in two ways. First, this study explored people's mental mappings between haptic properties and data types. This helped enrich the expressiveness of data representation. Second, this work used these mappings to improve haptic data representation. Several artifacts were developed to help people reflect on their activities and give them a comprehensive sense of data.

2 Related work

This section first reviews the studies on haptic perceptions, which provides insights on important haptic properties. Then it reviews the related haptic data representation literature, examining the typical types of haptic artifacts and their contexts of application.

2.1 Perception of haptic properties

People interact with their surroundings through various types of haptic sensations. The human haptic system is adept at perceiving the material characteristics of physical objects or artifacts through their cutaneous and kinesthetic subsystems (Lederman & Klatzky, 2009). The cutaneous subsystem perceives and integrates haptic stimuli involving mechanical forces, temperature exchanges, and chemical reactions, such as acids, while the kinesthetic system perceives motions of muscles and joints

(Rice & Albrecht, 2008). There are two types of neurons (i.e., slowly and rapidly adapting) that respond to a sustained stimulus. Slowly adapting neurons are pressure sensitive, whereas rapidly adapting neurons are vibration sensitive. Other than pressure and vibrations, the perception of texture is multidimensional and involves smoothness, softness, stickiness, and possibly warmth (Holliins et al., 1993; Hollins et al., 2000). It is worth noting that people have varied spatial resolution abilities and sensitivities to these haptic properties (Hale & Stanney, 2004). Vibration, for instance, has a lower spatial resolution than texture; friction has a higher chance of correct responses than stiffness for a given percentage difference (Wall & Brewster, 2003). These perceptual differences should be considered while designing haptic data representations.

Multiple manipulations with physical objects, such as lifting, pressing, lateral motion, enclosure, and static contact, are used to convey rich forms of haptic properties. Based on these perceived properties, people perceive physical objects by matching the haptic inputs to their prior knowledge of haptic representations (Lederman & Klatzky, 1987, 2009). The rich set of haptic information perceived through direct manipulation of physical objects can be used to convey data, facilitating data expression and comprehension (Rajko et al., 2016). Substance-related properties such as hardness, temperature, and weight give people an impression of the object such that heavy objects contain many substances. This impression enables the possibility of encoding data in the interpretation and experience of haptic properties (Hogan, 2018). People thus may describe the housing cost in a city as “heavy” and the most frequently discussed topics as “hot.”

2.2 Artifacts of haptic data representation

Several research descriptions refer to data representation using non-visual properties. These descriptions include physical data representation, shape-changing interfaces, haptic data representation, and data physicalization. Haptic and tangible interfaces facilitates exploration and relieves cognitive loads (Drogemuller et al., 2021), and supports a variety of tasks (Lee-Cultura & Giannakos, 2020). Multiple techniques have been developed to produce haptic sensations (Augstein & Neumayr, 2019). One common category of tangible data representation refers to physical diagrams and graphs that resemble their visual counterparts. The ways of encoding data in these studies are through utilizing geometric properties, similar to how visual visualization does (e.g., proportionally mapping the heights in a digital bar chart onto the sizes/heights/lengths of physical objects) (Hogan & Hornecker, 2016). Some other studies supplemented visual visualizations with haptic methods, e.g., force-feedback (Paneels & Roberts, 2010), displaying various graphs involving pie charts and line graphs (Ramloll et al., 2000; Wall & Brewster, 2006). Researchers have additionally employed technologies such as mid-air displays and shape-changing interfaces to generate dynamic physicalized graphs (Bhardwaj et al., 2021; Suzuki et al., 2019). These techniques utilize acoustic levitation to position lightweight objects in the air, and alter the length of each column to show charts and thus enable data exploration and manipulation (Follmer et al., 2013; Sahoo et al., 2016; Taher et al., 2015).

Apart from resembling of visual graphs, the multiple haptic properties discussed in section 2.1 provide possibilities of rich data representation. Hogan et al. (2017) proposed haptic probes to make sense of data. Vibration is the most frequently used haptic property; its waveform, frequency, and durations can all be employed as tactile icons to convey information (Brewster & Brown, 2004). The texture of an artifact can also be manipulated (Bau et al., 2009; Yu et al., 2016). Nakagaki et al. (2016) simulated haptic properties such as flexibility, elasticity, and viscosity. When adjusting the movement mode of modular columns, participants reported feeling different levels of flexibility and viscosity, according to a brief user study. Physikit integrates visual and haptic properties to provide an ambient way of perceiving air quality (Houben et al., 2016).

Researchers have successfully employed haptic properties in a variety of scenarios. However, it is worth noting that most artifacts employ a singular haptic property to present the value of certain data. This is in contrast to people's haptic sensations which have a wide range of haptic properties simultaneously. Furthermore, many data features such as sample size, variance, timing of collection are also critical for data comprehension. Facing the multiple data and rich haptic properties, the utilization of haptic sensations to augment data representation requires an empirically established understanding of people's interpretation and mental mappings between data and haptic properties, as well as their performance when perceiving these haptic properties (Isran et al., 2021).

3 Mappings between data and haptic properties

This section explores the issue of encoding data with haptic properties using an empirical approach. Several data and haptic properties were proposed, a set of cube prototypes was developed to produce a range of haptic sensations, and a user study of possible mental mappings between the data types and haptic properties were then examined (Figure 1). Specifically, we investigated participants' preferences of mappings between data and haptic properties as well as participants' performance while using these mappings to convey data. Two hypotheses on the mappings between data and haptic properties include:

1. People exhibit similar patterns when interpreting the data represented by haptic properties;
2. Both data types and haptic properties influence how people perceive data from haptic properties of artifacts. People will perform better with some specific mappings due to the ease of interpretation.

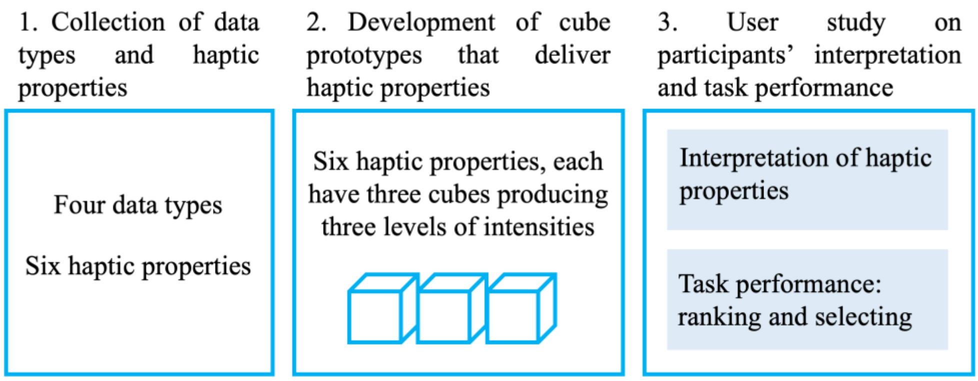

Figure 1. Steps to explore the mappings between data and haptic properties

3.1 Collection of data and haptic properties

An online questionnaire survey was carried out to gather an initial set of data types that worth to be conveyed in haptic data representation. 84 young adults (M=22.9 years old, SD = 5.6 years) responded voluntarily. 53 participants were undergraduate students, and the other 31 respondents worked in 19 different industries (such as accounting, education, healthcare, etc.). These participants are familiar with varied data types. In addition to basic demographic information (age, profession, and gender), the respondents were asked a free response question: "What types of data do you pay attention to for an event in daily life other than average value?" Four types of individual data variables (variance [51 times], rate of change [45 times], sample size [32 times], timing [29 times]) were proposed more than 28 times (one third of the respondents), and were included into further analyses. These data types were also chosen because they all are familiar concepts and were taught in the primary or secondary schools. Therefore, people with different levels of knowledge would have similar interpretations.

Six haptic properties were then collected referring to the reviewed articles in section 2.1 (Rice & Albrecht, 2008). These haptic properties involve vibration intensity, vibration frequency, airflow, weight, temperature, and texture. The six haptic properties are not comprehensive, while they cover varied properties and are easy to implement in multiple artifacts.

3.2 Development of cube prototypes that produce haptic sensations

The haptic properties of artifacts were simulated using cube prototypes. The cubes provided simple and same appearance for all haptic sensations in order to reduce the potential confounding effects of artifact forms. To ensure a distinguishable haptic variation, the magnitude values of each cube prototype were pilot-tested with five users, who were students recruited from online forum. Figure 2 shows the inner structures of the six types of cubes, with three levels of haptic magnitude, as well as images of the components that generate the haptic sensations. The detailed descriptions of these cubes are as follows:

- Weight. The perception of weight is produced using Kbaoele KB-20/15 electromagnets. With a steel pedestal under the cube, the magnetic force between the electromagnet and pedestal produces a feeling of weight when participants try to lift and move the cube. The cubes produced three weights (0.2 kg, 1.45 kg, and 2.7 kg). It is worth noting that we use electromagnets rather than change the real weight of the cube. The electromagnets occupied small space and were easy to product varied force. However, this did restrict participants' manipulation. Participants could not throw it to feel the "weight".
- Temperature. The temperature is produced using 10-ohm ceramic resistors. There is a piece of 0.1-mm-thick flat silver paper on each resistor to equalize the temperature across the upper surface of the cube. The temperatures of the resistor were 25°C, 40°C, and 60°C, respectively. Therefore, participants would not get hurt when touching the silver paper.
- Vibration intensity. The cubes contain Kuanyang 1226 vibrating motors to produce vibration. The rotating speeds of the motors are 12000 r/min. Vibration is generated by energizing the cubes with three levels of voltage (1.5 V, 2.5 V, and 5 V).
- Vibration frequency. The cubes also use Kuanyang 1226 vibrating motors to produce vibration. These cubes have vibration frequencies of 1.67 Hz, 3.33 Hz, and 10 Hz, respectively.
- Airflow. The fan cube includes a 60-mm-diameter fan and an 8YB DC motor. The fans rotate at three speeds (0 r/min, 7200 r/min, and 21600 r/min, respectively). The upper side of the cubes has 36 holes that allow airflow while blocking participants' eyesight so that the intensity of the airflow cannot be identified visibly.
- Texture. Texture is generated by 9 equally distributed screws in a 3 cm×3 cm area on the lateral side of a cube, which is covered by 0.2 mm-thick black tape. The diameter of the screws is 5 mm. The smooth cubes have a screw height of 0 mm, thus only offering the tape

texture. The middle ones have a screw height of 2 mm, and the rough ones have a screw height of 5 mm.

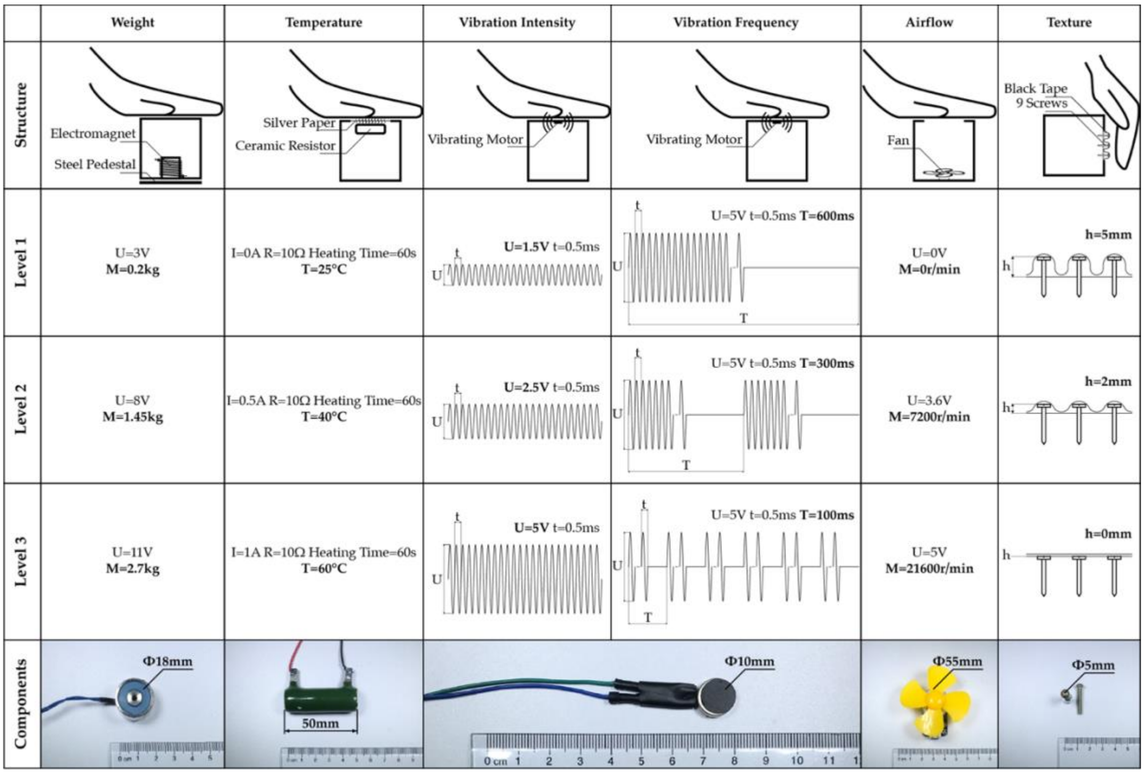

Figure 2. Inner structures of 6 types of cubes, 3 levels of haptic strength, and images of the components that generate the haptic sensations.

3.3 User study on participants' interpretation and task performance

Thirty-two participants took part in an exploratory user study on the mental mappings between data types and haptic properties of artifacts. They were recruited from an online forum, and all participants were university students from 23 majors. Considering the exploratory nature of our user experiment, we emphasize the internal validity (whether there are patterns when people associate haptic properties with data types) over the external validity of the generalizability of the initial findings to a wider population. Some compromises were made in this user study, using the convenience sample of university students, as some other initial experiments did. The priorities of demographic and application scenario considerations would be higher in our future experiments.

Each participation consisted of two experimental sessions, lasting approximately 35 min in total. Each participant was reimbursed 5 US dollars for their participation. Two participants were eliminated from the analysis because they did not complete the experiment. The remaining 30 participants had an average age of 23.0 years old (SD=2.7). Each experiment engaged only one participant at a time and was facilitated by an experimenter (Figure 3).

Figure 3. Experimental cubes and participants.

3.3.1 Participants' interpretations when presented with haptic properties.

Participants were presented with the cube prototypes. The sequences of haptic properties were counterbalanced using a Latin square design. For each haptic property, participants touched three test cube prototypes that provided three intensities of the same haptic property, selected a data type that could be expressed by this property, and explained the reasons for their choices.

3.3.2 Participants' performances when using haptic properties

Ranking and selecting task were chosen for performance evaluation because they are the fundamental activities in data sensory evaluation (Meilgaard et al., 1991). For instance, when participants experience multiple artifacts that represent forests in two different regions, they would rank the data value expressed by these artifacts (which have more and large trees?), and select artifacts that have similar values (which two have similar forest?). Therefore, if participants have high accuracy and short reaction time when ranking and selecting cubes, they might also perform well when interacting with these artifacts. If the performance is not affected by the data types, then participants' ranking and selecting are only affected by the feature of haptic properties. We thus chose appropriate mappings based on participants' interpretations. On the contrary, if the performance is affected by both haptic properties and data types, then we recommend mappings considering both participants' interpretations and performances.

With the six haptic properties and four types of data, there are 24 mappings between the haptic properties and data indicators. We examined these mappings one by one in a randomized sequence (Figure 4). In each run, we examine a specific haptic property presented values of the given type of data. A set of three test-cube prototypes conveyed the same haptic property but in three different levels of intensities.

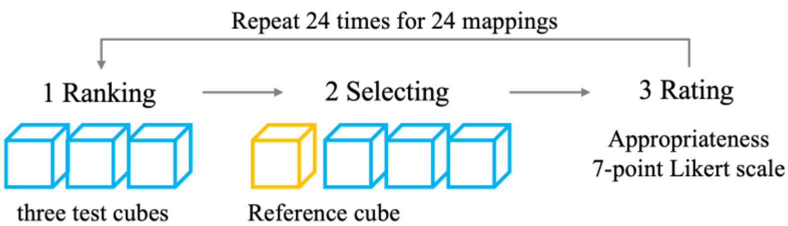

Figure 4. Experimental procedure.

Ranking data values of the three cube prototypes: After the facilitator's "start" command, the participant ranked the three cubes according to the perceived values of data from high to low, and reported "ok" as soon as s/he completed the ranking.

Selecting a specific data value from the three cube prototypes: After ranking, the facilitator presented a reference cube showing the same haptic property with the test cubes, and asked participants to select one from the three test-cubes which has equal data value with the reference cube. After the facilitator's "start" command, participants started selection and reported "ok" as soon as s/he completed the selection.

The same ranking and selecting procedures were repeated 24 times until all possible mappings between the six haptic properties and four types of data were tested. A two-minute break was provided after every six replicates.

3.4 Analysis and results

3.4.1 Participants' preferences of mappings in interpretations.

Table 1 shows the frequency of haptic properties that were selected as appropriate to express a data type. Multinomial tests were performed for each haptic property. A value of 0.05 was used as the cutoff for significance. The p values were also adjusted based on False Discovery Rate. The results suggested that participants had similar preferences of data types when presented cubes for haptic properties of air ($\chi 2 = 13.47$, $p = 0.004$), vibration frequency ($\chi 2 = 23.07$, $p < 0.001$), vibration intensity ($\chi 2 = 9.20$, $p = 0.027$), and weight ($\chi 2 = 29.47$, $p < 0.001$). The mapping AIR-SS, AIR-ROC, FREQ-VAR, FREQ-ROC, INT-VAR, and WT-SS are preferable by participants. Also, it is worth noting that although participants have a broad interpretation of temperature and texture, they prefer to use these two properties to convey timing of data collection ($\chi 2 = 22.11$, $p < 0.001$). The above mappings provided reference of haptic properties when we have a certain data type to be presented, which include:

- Variance: frequency, vibration intensity;
- Timing of data collection: temperature, texture;
- Sample size: air, weight;
- Rate of change: air, frequency

Table 1. Frequencies at which participants selected haptic properties to represent data.

	VAR	TIME	SS	ROC	χ^2	FDR adjusted P value
AIR	2	3	13	12	13.47	0.008
TEMP	4	11	6	9	3.87	0.331
TEXT	9	9	4	8	2.27	0.519
FREQ	10	0	3	17	23.07	<0.001
INT	14	3	5	8	9.20	0.0405
WT	6	1	20	3	29.47	<0.001

(Green marks the selected properties. VAR: variance, TIME: timing of data collection, SS: sample size, ROC: rate of change, AIR: airflow, TEMP: temperature, TEXT: texture, FREQ: vibration frequency; INT: vibration intensity, and WT: weight.)

Participants provided two types of reasons for selecting the data: the haptic property symbolizes some metaphors, or the value of the haptic properties corresponds to the value of the data type. Typical reasons are listed in Table 2.

Table 2. Reasons for selecting data types represented by specific haptic properties

		Reasons
VAR	**INT**	The stronger the vibration is, the more unstable the data.
	FREQ	The higher the frequency is, the faster the change.
TIME	**TEMP**	The data becomes colder with time.
	TEXT	The older the data is, the more creased the surface.
SS	**WT**	The amount of data affects the weight
	AIR	Stronger wind means more data.
ROC	**FREQ**	The higher the frequency is, the faster the change.
	AIR	The faster the wind is, the faster the change.

3.4.2 Participants' task performance.

The participants' accuracies and time of completion in ranking and selecting tasks indicated the appropriateness of the mapping. The participants achieved an accuracy of 83.78% for ranking tasks and 84.86% for selecting tasks.

Participants spent an average of 10.12 seconds on ranking tasks and an average of 6.04 seconds on selecting tasks. This time of completion in ranking tasks was affected both by the haptic properties ($F=13.46$, $p<0.001$) and the data types ($F=3.22$, $p=0.028$). The time needed to complete the selecting tasks was affected by the haptic properties ($F=4.50$, $p<0.001$). Ranking tasks and selecting tasks that used vibration frequency needed more time than tasks using other properties (ranking: 15.52 seconds, selecting: 7.77 seconds). The times for ranking correctly and incorrectly did not have a significant difference.

3.4.3 Recommended mappings between haptic properties and data

The results of participants' interpretation and performance indicated that participants did have similarities in the mental mappings between haptic properties and data types. Meanwhile, participants' ranking and selecting performances were affected by both haptic properties and data types, indicating the existence of appropriate mappings in haptic data expression. Table 3 summarized participants' performance and ratings for the mappings summarized in section 3.4.1. It is worth noting that two haptic properties have similar performance for the data type TIME. Five mappings in green have high preferences and also achieved great performance, which were recommended when developing haptic artifacts.

Table 3. Preference and performance of the haptic properties for the four data types.

		FR	RT	RA	ST	SA	R
VAR	INT	14	9.1	93.6%	5.3	96.8%	5.0
	FREQ	11	12.8	70.0%	6.7	76.7%	4.4
TIME	TEMP	11	11.2	80.7%	5.1	83.9%	5.3
	TEXT	9	10.3	87.1%	6.1	87.1%	4.3
SS	WT	20	7.8	93.6%	6.3	90.3%	5.8
	AIR	13	8.3	87.1%	5.9	74.2%	4.2
ROC	FREQ	17	15.9	61.3%	8.9	83.9%	5.5
	AIR	12	10.5	87.1%	6.0	86.9%	4.6

(Green marks the recommended mappings. FR: frequency; RT: ranking time; RA: ranking accuracy; ST: selecting time; SA: selecting accuracy; R: ratings.)

4 Design workshop that “play with data”

The user study suggested some certain haptic properties may appropriately convey four data types from an empirical perspective. This section describes our generative endeavors: a design workshop invited six product designers to brainstorm and create data artifacts that convey data types of the user study. Haptikit, a modular toolkit, was developed to facilitate the prototyping of data artifact. Designers, with the assistant of Haptikit, envisioned haptic data presentation to enrich people’s experience and support their activities.

4.1 Haptikit as a toolkit of haptic data representation

Haptikit was developed for this workshop. Carton is a familiar material to product designers, who can easily adapt the form of Haptikit into any appearance to fit their design purpose. The hardware consisted of two parts: a controller and actuators. The controller, built based on Arduino Uno, receives data from the software and sends them to appropriate actuators. There are five actuator modules in the toolkit, including the height module, the temperature module, the weight module, the vibration module, and the airflow module. The techniques used to build the vibration, temperature, and airflow modules are similar to those in prior experiments. The height module (Figure 4-d) can change heights (range from 105 mm to 185 mm) with a stepping motor. The details of the five modules are shown in Figure 5.

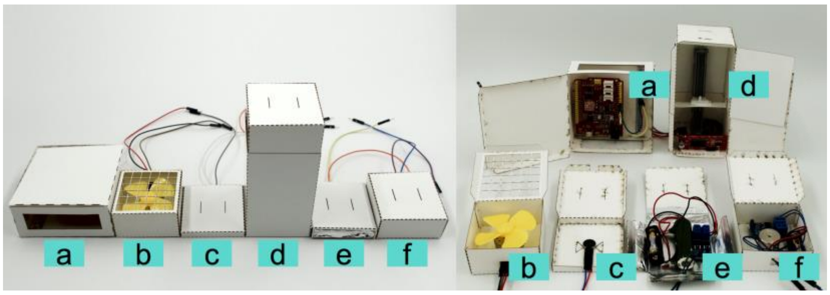

Figure 5. The appearance and inner structure of Haptikit: a) Arduino, b) airflow module, c) vibration module, d) height module, e) temperature module, and f) weight module.

We developed software using Processing. This software supports data management and transmits the data to Haptikit. Users arrange the data they want to represent in a CSV file (Figure 6), upload them, and drag the data to the toolkit modules shown in Figure 7. Then, users download the program to the controller and use the data to control the actuators in artifacts.

	A	B	C	D	E	F	G	H	I	J
1	Mean1	Variance1	Time1	SampleSize1	ROC1	Mean2	Variance2	Time2	SampleSize2	ROC2
2	15.1	1.65	2010.1	60	0.015	20	2.66	2012.1	66	0.035
3	15.5	1.45	2010.2	60	0.026	20.1	2.54	2012.2	66	0.005
4	16	1.44	2010.3	60	0.032	20.2	2.23	2012.3	66	0.005

Figure 6. Sample CSV file

Figure 7. The software interface supporting the control of Haptikit.

4.2 Workshop procedure and prototypes

We invited six product designers to design artifacts using Haptikit (4 males and 2 females, mean age of 27.5 years, SD=3.4). These participants are all product designers that have experience of designing physical artifacts. The design process was divided into three stages and lasted two days: (S1) An introduction. Participants were introduced to the mappings, the Haptikit, and some examples of artifacts. (S2) A 30-minute conceptual design process. Participants chose whatever data and haptic properties they like to develop design concepts. (S3) Prototyping in the other day. The design workshop resulted in five design concepts with artifacts. It is worth noting that the data comes from events and activities in daily life. Besides, designers in this workshop build prototypes with cubes to show the possibilities in a limited time. The appearance could be modified to match people's preference such as models of themselves. The five artifacts act as an initial example that enriches haptic data representation and should be further explored in following studies.

When using haptic properties to present multiple data types in an artifact, designers thought the recommended mappings were reasonable using a 7-point Likert scale (average rating=6, SD=0.89). One designer said, *"Vibration gives me a sense of chaos, and variance also reflects the degree of dispersion in the data"* [Designer 1]. The designers also proposed that the mapping between time and temperature was appropriate and vivid. "*There is some remaining heat when a machine just finishes its work; the heat then dissipates as time goes on"* [Designer 3]. "Just imagine the cooked food, the hot food indicates that it is freshly cooked. If the food is cold, some time has passed since cooking" [Designer 5].

Designers in workshops explored varied combinations and forms of haptic expression, displaying substantial freedom in design ideas and artifacts (Table 4 and Table 5), as shown in Figure 8. These artifacts present extra information that help with timely feedback (singing practice), reflection (ads design), data understanding (evolutionary history of animals), and decision making (consumption in supermarkets).

Table 4. Haptic properties participants selected to represent data.

Artifacts	**Haptic properties**	**Data types**
Design A: Ad Trends	Vibration intensity Temperature Weight	Variety of ad styles. Ad design time. Number of ads in a specific style
Design B: Daily data Feedback.	Vibration intensity Temperature Weight Airflow	Differences among people's running distance. How long since the user has run or consumed water. How many times user ran/drank. The trend of people's running performance
Design C: Singing Practice.	Vibration intensity Airflow	Differences between a musician's pitches and the standard ones of a song. Crescendo and decrescendo of a song
Design D: Evolutionary History Education	Vibration intensity Temperature Weight Airflow	Variance of quantity in the last 50 years. Active periods in evolutionary history Number of species Change of number of animals
Design E: Supermarket Shelf.	Temperature Airflow	Freshness of goods Sales trend of the goods in supermarkets.

Figure 8. Artifacts developed in the workshop

Table 5. Artifact description

Artifact Description	Benefits proposed by designers
Design A: Ad Trends. Each artifact shows the variety of ads in an ad style (vibration), the number of ads (weight), and when these ads were designed (time). Users could find heavy, vibrating but cold locations to restart the old trends, or follow light, still but hot ones to cut in new trends. When the location is heavy, still but hot, this style might not last long. In this way, users get a holistic feeling of the difference between styles. Rather than visual search of numerous ads, they can simultaneously follow multiple properties to locate what they want.	Holistic feeling of ad data, reduce the load of vision
Design B: Daily data Feedback. Show the data of people's sleep, water intake, and energy consumption. If the artifact vibrates a lot and is cold, users might take long distance running at one time rather than keeping a balanced running habit. Users know that they could not complement this through running a lot now (although this did increase the average running distance, but artifact will still vibrate), they should run appropriate distance at a set pace, and increase the distance step by step. Therefore, users would have a hot, heavy artifact with soft wind. It is worth noting that there is not a best status, users could raise an artifact with strong wind (large improvements of running each time), or a light and calm one (regular exercise with mild intensity).	Artifacts are interesting and friendly
Design C: Singing Practice. The vibration intensity shows the difference between people's pitches and the standard ones, and the airflow provides a reminder of the crescendo and decrescendo in the song. Therefore, the users know which parts need modification and practice.	Two advantages: serve as a subtle reminder, private and covert information
Design D: Evolution History Education. A species of animal could be light with strong wind, which indicates endangered but protected ones such as panda. An artifact could be light but stable, or heavy but vibrating, the later indicating that this species is easily affected by climate and human activities. When the columns of species cool and vibrate and the wind decreases, the species are in danger. It is easy to understand the evolution history of a species by touching and feeling the artifact.	Kids are willing to play with haptic objects
Design E: Supermarket Shelf. The artifact could have strong wind to show customers are interested in specific goods and buy a lot recently. When customers compare goods on a shelf, they can easily know which one has sold better and which one is fresher. This artifact encourages people to have more physical contact with goods.	Entertain customers in a hurry

5 Discussion

This article conducted a user study to explore people's mental mappings between haptic properties and data types. The recommended mappings supported the development of artifacts that offered a holistic representation of activity data. This as an initial exploration might enrich people's data experience of activities and events.

5.1 The empirical mappings between haptic properties and data types

Participants did need different haptic properties to perceive different aspects of the data. Their preferences were similar. As shown in table 1, participants had similar opinions when interpreting the value conveyed by haptic properties. This similarity comes from the symbols/metaphors that participants used to interpret haptic properties, and the correspondence between the value of the haptic properties and the value of the data type. Participants proposed that heavy artifacts have data of large sample size, unstable data might vibrate, and prior data become “cold”.

Participants also have varied performance with different mappings between data and haptic properties. The time needed to complete tasks differed for multiple mappings. The results indicated the effect of both data types and haptic properties. No single haptic property performed well in all cases. Therefore, it is preferable to choose appropriate mappings considering both participants’ preference and performance.

5.2 Holistic haptic data representation with multiple properties

The workshop invited participants to design artifacts with the haptic properties of weight, temperature, airflow, and vibration. These artifacts make use of haptic properties and present extra information that help with timely feedback (singing practice), reflection (ads design), data understanding (evolutionary history of animals), and decision making (consumption in supermarkets). The broad range of situations and the rich data characteristics that can be conveyed reveal the potential and effectiveness of using haptic properties to express multiple data types.

It is worth noting that the data types presented by these artifacts are usually ignored before, while they are tightly correlated and valuable. The variance, sample size, timing of data etc. are all important factors when building a deep understanding of data. In the running example, other than running distance, the timing of running and variation of running distance are both important factors of healthy exercise. In this case, a stable (low variance) and regular (fresh timing) exercise is represented by a warm and calm box. When the box cools down (temperature-time: long time after the last run), become light (weight-sample size: less running), or vibrates (vibration-variance: high variance of running distance), it indicates that users exercise irregularly and unstably.

The holistic feeling of data conveyed by the artifact is another important strength of haptic data representation. When we manipulate an artifact, multiple haptic subsystem works simultaneously and provided an embodied haptic experience, supporting a holistic feeling of data. Users can just feel the trend during manipulation without the need to discriminate specific data types. The boxes in evolutionary history of animals could present an overall state of the animal species. Even though a child may not know the definition of variance and rate of change, he/she may experience the die out of a species through a colder and more static box. Another example is the artifacts for ad design, when moving the dot around, users only need to chase the change of temperature, wind, vibration, and weight to find the hottest design trend. Here the “energy” of the artifact corresponded to the popularity of the design trend.

The modular toolkit supported development of prototype based on people’s needs and invoked a new way of experiencing data. We found that the form of paper box induced an atmosphere of rapid prototyping. The participants used paper graphs and tags to represent animals and activity categories in this workshop and painted the paper box to mark the data of ads. Haptikit might thus act as an inspirational tool and enable a broad exploration of new possibilities for crowd participants. Furthermore, the paper box provides a basic appearance form that could be modified and adjusted easily based on the contextual requirements. Therefore, Haptikit can be integrated with plush toys as a friendly form to convey data for children or be covered with silica gel for artifacts used under water. New modules resembling Lego bricks can be developed to enlarge the applicable domain of Haptikit.

Lastly, the value of data representation methods is inherently affected by the nature of data. When compared with data from simple events (such as a single student's walking distance), variance and sample size hold higher value in complex data such as accident reports and stock prices. Such data typically measure events over a specific period or across diverse contexts. Furthermore, the data representation may also pose constraints on user demographics. Users of haptic data representation need to have familiarity, or at least an interest in these data types. Common applications can be found in contexts such as museums, exhibitions and educational settings.

6 Conclusion

Haptic data representation offers a promising avenue for enhancing data exploration and communication. Although existing studies on haptic data representation and data physicalization developed artifacts that enabled interaction of multiple haptic properties, the data types assigned to haptic properties seem to be limited. Key information facets such as variance, trend, and sample size, are often under-represented, with scant attention paid to the concurrent representation of multiple data aspects.

This article conducted an exploration on expressing multiple data types through artifacts' various haptic properties. Specifically, we investigated participants' preferences in selecting haptic properties to represent data, and measured their performance in ranking and selecting tasks. Then, we conducted a design workshop to delve deeper into the potential of haptic data representation. The user study and workshop together validated the existence of mappings between haptic properties and data types, and the benefits of coherently representing multiple data types within an artifact. In this way, our work broadens the data types that haptic properties could represent, provides a way for creating a holistic impression of data and enriching the application of haptic data representation.

This article is an initial exploration. Future work will focus on assessing the applicability of the mappings, and explore the benefits of concurrent data representation across varied contexts. Additionally, this article used cubes to gauge participants' mappings and develop artifacts, perceived through figures and palms. How these mappings might vary across multiple scales of artifacts and interactive methods worth further exploration.

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