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Widgets: A new Set of Parametrically Defined 3D Objects for Use in Haptic and Visual Categorization Tasks

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Abstract

Introduction. Most research to date on human categorization ability has concentrated on the visual and auditory domains. However, a limited–but non-negligible-range of studies has also examined the categorization of familiar or unfamiliar (i.e., novel) objects in the haptic (i.e., tactile-kinesthetic) modality.

Objective. In this paper, we describe how we developed a new set of parametrically defined objects, called *widgets*, that can be used as 3D (or 2D) materials for haptic (or visual) categorization purposes.

Method. Widgets are unfamiliar complex 3D shapes with an ovoid body and four types of elements attached to it (eyes, tail, crest, and legs). The stimulus set comprises 24 objects divided into four categories of six exemplars each (the files used for 3D printing are provided as Supplementary Material).

Results. We also assessed and demonstrated the validity of our stimulus set by conducting two separate studies of haptic and visual categorization, involving participants of different ages: young adults (Study 1), and children and adolescents (Study 2). Results showed that humans can categorize our 3D complex shapes on the basis of both haptically and visually perceived similarities in shape attributes.

Conclusion. Widgets are very useful new experimental stimuli for categorization studies using 3D printing technology.

Keywords: haptic; vision; categorization; 3D printing technology

Résumé

Introduction. La plupart des recherches à ce jour sur la capacité de catégorisation humaine se sont concentréres sur les domaines visuel et auditifs. Cependant, un éventail limité -mais non négligeable- d'études a également examiné la catégorisation d'objets familiers ou non familiers (c'est-à-dire nouveaux) dans la modalité haptique (c'est-à-dire tactilo-kinesthésique).

Objectif. Dans cet article, nous décrivons comment nous avons développé un nouvel ensemble d'objets définis paramétriquement, appelés *widgets*, qui peuvent être utilisés comme matériaux 3D (ou 2D) à des fins de catégorisation haptique (ou visuelle).

Méthode. Les *widgets* sont des formes 3D complexes non familières avec un corps ovoïde et quatre types d'éléments qui y sont attachés (yeux, queue, crête et jambes). L'ensemble des stimuli comprend 24 objets divisés en quatre catégories de six exemplaires chacun (les fichiers utilisés pour l'impression 3D sont fournis comme matériel supplémentaire).

Résultats. Nous avons également évalué et démontré la validité de notre ensemble de stimuli en menant deux études distinctes de catégorisation haptique et visuelle, impliquant des participants d'âges différents: des jeunes adultes (étude 1) et des enfants et des adolescents (étude 2). Les résultats ont montré que les humains peuvent classer nos formes complexes 3D sur la base de similitudes perçues à la fois haptiquement et visuellement dans les attributs de forme.

Conclusion. Les *widgets* sont de nouveaux stimuli expérimentaux très utiles pour les études de catégorisation utilisant la technologie d'impression 3D.

Mots clés: haptique; vision; catégorisation; technologie d'impression 3D

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1. Introduction

There is a longstanding tradition of research on human categorization behavior (see, for example, Rosch, 1978), as categorization is seen as a fundamental process of human cognition. Categorization is important to study because it permits abstract thought and promotes expansion of knowledge to novel situations. It has an early onset but develops remarkably during childhood (see Sloutsky, 2010 for a review). There are two competing models of how humans represent categories: prototype models and exemplar models (see Ashby & Maddox, 2005). According to *prototype* models (Edelman, 1998; Homa, 1984; Posner & Keele, 1968; Rosch, 1978), people represent a given category by forming a summary representation that corresponds to a central tendency of all of the experienced members of that category. Categories are therefore each represented by a prototypical object or virtual average. In these models, classification decisions are based on the similarity of an item to the prototype. *Exemplar* models (Medin & Schaffer, 1978; Nosofsky, 1992) assert that people represent a given category by storing the individual members (i.e., exemplars) of that category as separate traces. Categories are thus represented by the representation of all previously encountered objects. In these models, classification decisions are based on the similarity of an item to these stored exemplars.

While most research to date on human categorization ability has concentrated on the visual and auditory domains, a limited–but non-negligible-range of studies has also examined the categorization of objects in the haptic (i.e., tactile-kinesthetic) modality. As demonstrated by Lederman and Klatzky (1990; Klatzky, Lederman, & Metzger, 1985), the haptic modality is an expert system for identifying familiar objects. These authors showed that adults can quickly (< 2 s) and accurately (nearly 100%) recognize common everyday objects (e.g., ashtray, glasses, comb) through haptics. Interestingly, Lederman and Klatzky found that the haptic system was more tuned to detect and extract information about the "material" properties of objects (i.e., properties that are independent from the geometric structure of objects, such as texture, hardness or temperature) than the "formal" properties of objects (i.e., properties that are coded spatially, such as size and shape). Similarly, Haag (2011) found that adults were impressively good at classifying familiar objects (miniature toys representing animals) using the sense of touch. In this study, university students were free to explore 20 hand-held toy replicas of animals (e.g., bear, cow, dog, elephant, horse, lion) by inserting both arms and hands inside a cardboard "blind box" (without viewing the objects examined). They had to sort the stimuli three times, one each for the dimension of size (big/small), domesticity (wild/domestic) and predation (carnivore/omnivore). Mean categorization errors were low overall, varying between .08 (for size) and .21 (for predation).

These findings indicate that humans are able to categorize objects by touch, using pre-established semantic knowledge, but what happens when the objects are novel or unfamiliar, meaning that haptic categorization has to consider object-intrinsic properties such as shape, rather than semantic knowledge? We selected and reviewed eight papers that were directly relevant to this issue (Cooke, Jäkel, Wallraven, & Bülthoff, 2007; Gaissert, Bülthoff, & Wallraven, 2011; Homa, Kahol, Tripathi, Bratton, & Panchanathan, 2009; James, Shima, Tarr, & Gauthier, 2005; Lacey, Peters, & Sathian, 2007; Norman, Norman, Clayton, Lianekhammy, & Zielke, 2004; Schwarzer, Küfer, & Wilkening, 1999; Yildirim & Jacobs, 2013), and summarized the main characteristics of the methods they described (see Table 1). All these studies used unfamiliar (i.e., novel) 3D stimuli as material for haptic categorization or object recognition purposes. Restricting the material in this way allowed the objects' perceptual characteristics to be disentangled from their semantic aspects. Because the stimuli had no semantic labels, participants were forced to rely exclusively on their intrinsic properties (e.g., shape) to perform the task.

As summarized in Table 1, the eight selected studies used a variety of methods: some used the category-learning task originally developed by Ward and Scott (1987) (Studies 1, 6 and 8), recognition tasks (Studies 2, 3 and 4) or categorization tasks (Studies 5 and 7). Note that, in most cases, a learning/training phase preceded the main task. Some of these tasks were used to assess haptic perception *per se* in adults (sighted/blind) and in children (Studies 1, 3 and 6); but, in most cases, they served to investigate visuo-haptic and cross-modal transfer between vision and touch in adult participants (Studies 2, 4, 5, 7 and 8). Therefore, haptic perception studies are a minority in the field, where cross-modal visual-haptic research dominates.

-Insert Table 1 about here-

Stimulus size differed across the studies (see Table 1), but the objects were generally small enough for them to be easily grasped and handled. The exploration mode was either free (Studies 2, 3, 4, 6, 7 and 8) or constrained by specific exploratory procedures (see Lederman & Klatzky, 1987), such as enclosure (Study 1) or contour following (Study 5). Stimuli used in the studies (see Table 1) systematically varied on the shape attribute, which is known to be important for object categorization-at least in adults (Schwarzer et al., 1999), but some varied both in shape and in additional dimensions, such as texture, size, and/or weight (Studies 1, 4, and 5). Interestingly, these stimuli were of three main types (see Table 1): A first type involved simple abstract geometric objects, like building blocks that were handmade (Studies 1, 4 and 6). A second type comprised more complex geometric shapes that mimicked natural objects, like bell peppers, spheres, or shell-shapes objects, constructed using either replicas of natural forms (Study 2) or computer graphics with 3D printing technologies (Studies 5 and 7). A third type included complex geometric shapes that were entirely artificial and parametrically-defined, like Fribbles and Greebles, both created using computer graphic and 3D printing devices (Studies 3 and 8). Fribbles are artificial, three-dimensional, complex shapes that mimic the structures of real-world animals (Williams, 1987). There are 12 species, each of which is constituted by a central body structure with four attached appendages. Greebles are artificial, three-dimensional, complex nonface stimuli that were created as control stimuli for faces. There are 5 families x 2 genders, each of which is constituted by a vertically oriented central part with four protruding parts.

It came out from this corpus of studies that humans are able to learn or form haptic categories focusing on shape attribute (Studies 1, 5, 6 and 7), as well as they are able to compare or transfer shape information across vision and touch (Studies 2, 3, 4, 5, 7 and 8). However, if part of this literature reveals that humans are surprisingly good at learning and forming haptic categories of unfamiliar (i.e., novel) 3D objects, it is worth noting that these abilities were observed under specific conditions where participants were able to learn and familiarize themselves with the stimuli before dividing them into categories. It is thus not clear whether similarly good performances would have been observed under less favorable test conditions (i.e., no prior learning or familiarization). In addition, the literature on haptic categorization abilities says little about the nature of the underlying mechanisms.

This may, partly, be due to the nature of the stimuli used in the reviewed studies. Indeed, existing stimuli sets (see Table 1) ranged between simple and handmade geometric forms to complex natural and artificial shapes, which situate somewhere along continuums of controllability and generalizability to the external world. Research on the mechanisms of haptic categorization requires stimulus sets with both a high generalizability (to the types of objects humans encounter in the world) and a high controllability. Whereas simple geometric forms (Studies 1, 4 and 6) present high controllability but lack generalizability, complex natural shapes (Studies 2, 5 and 7) present higher external validity but limited controllability.

By comparison, complex artificial stimuli (Fribbles and Greebles from Studies 3 and 8) represent potentially fruitful sets of stimuli that meet the demands of high controllability and high external validity necessary to the investigation of the nature of haptic categorization mechanisms. Unfortunately (at least to our knowledge), Fribbles and Greebles have not been used as stimuli in haptic categorization tasks so far, and we therefore have no evidence for their applicability to haptic categorization study. Indeed, Yildirim and Jacobs (2013) used Fribbles as materials for cross-modal transfer in a category learning paradigm, and James et al. (2005) tested Greebles as materials for haptic recognition in two adult participants only.

In our view, complementary to Fribbles and Greebles, there is a need to design a new stimuli set to examine humans' ability to categorize unfamiliar and complex 3D shapes in the haptic modality. Fribbles and Greebles are arguably interesting artificially-generated stimuli for research, but beside offering advantages, they also present limitations. Both stimuli sets came from vision research, which offers the advantage that these objects have a very large body of results in the visual domain. Both kinds of stimuli sets were initially pictures of 3D novel objects, with a family-like structure (Fribbles were pictures of biological-looking novel objects originally developed by Williams (1987) for the study of visual object recognition, while Greebles were designed as non-face stimuli and used as pictures in research on visual perceptual expertise by Gauthier and Tarr, 1997). But, in counterpart, because these objects were created to specifically address visual research questions (i.e., how do we recognize objects visually? how do we become expert in face reading and face recognition?), their adaptability or usability for haptic research issues is not guaranteed. No need to say that huge differences exist between vision and touch: basically the perceptual field of touch is much more limited compared to vision and its apprehension is more successive and fragmentary (Heller & Gentaz, 2014; Lederman & Klatzky, 2009). For instance, the non-face structure of Greebles, including variations in gender and families (race), may have only limited meaning for haptic research studies. Finally, it should be noted that both existing tangible stimuli sets (Fribbles and Greebles) are subsets of larger original visual corpus[1], a potentially concerning fact as we ignore the extent to which restricting an initial stimulus set may have changed (or not) its family-like structure. For these different reasons, we believe that a new set of tangible 3D novel objects would be useful for haptic research studies.

From this perspective, and in line with the literature reviewed above, the contribution of the present study was twofold. First, we designed and created a new set of parametrically defined objects called *widgets*, that is, complex 3D shapes with multiple parts and spatial relations between these parts. To achieve this, we used computer graphics and 3D printing technology. As we have seen, the use of this technology is quite recent in the domain of haptic perception and categorization research (see selected papers in Table 1). It is useful because it makes it considerably easier to produce and reproduce controlled artificial stimuli (i.e., objects with highly controlled properties, compared with handmade or manually assembled objects). Importantly, our set of objects was designed to have a categorical structure, with each object being an exemplar of a category defined by a set of commonly shared features. Widgets are a novel set of animal-like stimuli, with anatomical structures like those of animals (see Figure 1). We choose these types of animal-like objects because they have desirable properties for research: they mimic the properties and complexities of real-world stimuli, and have both experimental control and generalizability to the real world. Unlike previous datasets (e.g., the Fribble dataset; Yildirim & Jacobs, 2013), we provide detailed information about the component parts of each object and the rules for constructing our categories and their exemplars. It is important for readers to have this knowledge if we want to relate human categorization performances for widgets to the objective physical

[1] In 2005 and 2013 respectively, subsets of tangible 3D Greebles (n = 30) and 3D Fribbles (n = 40) were created by turning part of the original and large sets of 3D pictures into smaller sets of 3D objects, using computer graphics and 3D printing techniques.

properties of the material. Using a 3D-printing process, we turned our widget designs into physical objects that could be handled, and were thus usable as a material for a variety of haptic (and/or visual) categorization studies. With a view to promoting research on haptic categorization, we have made our widget files freely available to researchers worldwide (see Supplementary Material[2]).

Second, we conducted studies to test the validity of our material with different age groups and designs. More specifically, we ran two separate studies. In the first one, we asked two independent groups of 30 blindfolded sighted adults to categorize our new parametrically defined set of objects (N = 24), using either their sense of active touch (haptics) or their sense of vision (sensory modality was a between-participants factor). We used a categorization task with no prior familiarization or learning, because of its relative simplicity and the high ecological validity of spontaneous categorization (Milton & Wills, 2004; Picard, Dacremont, Valentin, & Giboreau, 2003). Following the example of Gaissert et al. (2011), we set up two different instructions for categorization: 1) form as many groups as you want (free categorization); and 2) form exactly four groups with six exemplars in each group (cued categorization). We were interested in comparing the performance levels of participants with and without information about how to categorize the set of objects. In the second study, we administered a cued categorization task in which we asked younger participants (20 children of 7 years and 20 adolescents of 14 years) to categorize part of our stimulus set (N = 16), either in the haptic then the visual modality, or vice versa (sensory modality was a within-participants factor). Here, we wanted to test success rates at categorizing widgets in children and adolescents, asking whether our material could also be used with young people. Because these participants were younger, we had to adapt the procedure and material to their age.

[2] The supplementary material associated to the manuscript can be found at the following persistent URL: https://osf.io/q4p3g/

Therefore, Study 2 is not an extension or a follow-up study of Study 1, but stands as an independent novel study. First, based on the results of pretests, we decided to use only cued categorization, which we assumed would facilitate categorization among children and adolescents. Second, again based on the results of pretests, we decided to restrict our set of material to 16 widgets (and not 24 as in Study 1), which we assumed would reduce task demands, notably in terms of working memory load. Third and last, we decided to use sensory modality as a within-participants factor (meaning that our young participants would have to perform the categorization task twice: once in the haptic modality and once in the visual modality, the order being counterbalanced across participants). Compared to Study 1, we changed the design in this respect because we were also interested in testing possible modality order effects where participants performed the categorization task first in one modality, then the other. Of course, changes in both age and design (between Study 1 and Study 2) did not allow for a direct comparison of the findings obtained in both studies. We therefore tackled and discussed separately the main results of Studies 1 and 2 (see Discussion section).

2. Creation of 3D parametrically defined stimuli

We first generated 24 3D objects divided in four categories of six exemplars each (see Fig. 1). These objects were first built as 3D images, using Blender-3D software, then printed using a 3D printer (Pearl-3D). 3D printing is a process of creating solid and tangible 3D objects from a digital file. Objects are printed layer by layer, by laying down successive layers of material (filament made with virgin resin).

2.1. Stimuli characteristics

The widgets were parametrically defined animal-like objects. As illustrated in Figure 1, each object had a semi-ovoid base to which four elements were attached (a-d). Despite the absence of semantic labels attached to our objects and their component features, for practical reasons, we decided to give each element a name. Accordingly, we named element (a) *eyes*, element (b) *tail*, element (c) *crest*, and element (d) *legs*. The semi-ovoid base was referred to as the *body*. These elements each belonged to a given category of objects, which conferred on them a family resemblance or kinship. For instance, all the exemplars of Category 1 had two *eyes* and two *legs*, whereas those in Category 2 had a single *eye* and three *legs*. Thus, within a given category, all the exemplars were different, but constructed on the basis of the same elements. We selected these specific appendages (i.e., number and types) because a) their types were likely components of novel animal-like stimuli and could be fully manipulated, and b) their number was comparable to that used in previous stimulus sets (e.g., both Fribbles and Greebles have four types of appendages) and did not exceed much the limitations of tactile short-term memory (see e.g., Gilson & Baddeley, 1969; Picard & Monnier, 2009).

To distinguish between these objects, we created two modes of presentation for each element (a1 and a2; b1 and b2; c1 and c2; d1 and d2), which varied with respect to the element's shape or position. For each category, we created a total of eight different primitives (2 modes x 4 elements). For instance, as shown in Figure 1, all the objects in Category 1 had two eyes, but some exemplars had eyes that were close together (a1), whereas others had eyes that were far apart (a2). In the same category, all the objects had two legs, but some exemplars had round legs (d1), whereas others had rectangular legs (d2). In each category, half the elements displayed changes in shape and half in position, and the type of change varied from one category to another (e.g., in Categories 1 and 3, eyes and crests varied in position, and tails and legs varied in shape; vice versa for Categories 2 and 4).

-Insert Figure 1 about here-

2.2. Construction rules

The rules for constructing objects from the primitives are described in Table 2. These rules were exactly the same for all categories, and stipulated that (1) there are six different objects within a family, (2) each object within a family is composed of four primitives a, b, c, and d, either in mode 1 or in mode 2, and (3) each primitive (in modes: a1, a2, b1, b2, c1, c2, d1, and d2) appears three times across the six exemplars of a given category. Note that we intentionally selected these rules, so that exemplars within a family were all unique whilst being made from a single set of features. With these construction rules, the number of primitives shared by pairs of exemplars of a given category varied between zero and three (see Table 3). As a result, some exemplars were more alike than others. The varying similarity within one family was not intentionally selected as such, but consecutive of the construction rules we set up for creating objects with a family-like structure. Thus, for a given category, the resemblance between exemplars was variable, but this variability in kinship was constant across categories.

-Insert Table 2 about here-

-Insert Table 3 about here-

2.3. Final stimulus set

The full set of 3D widgets comprised 24 objects, and had the following measurements. The semi-ovoid basis measured 10 x 6.5 cm (held constant for all 3D widgets). Depending on the primitives defining the exemplar, the final size of the 3D objects varied between 11 and 17.5 cm in length, 6.5 and 9.5 cm in width, and 3.5 and 5 cm in height. Thus, each object could easily be grasped and manually explored.

We also printed visual analogs of the 3D widgets, to serve as 2D material in visual (control) categorization tasks. To this end, we printed and laminated gray-scale pictures of the stimuli (see Fig. 1). The objects in these pictures were presented in a three quarters view, inside a 15.5 x 13 cm rectangle. The size of the visual analogs was roughly comparable to the actual 3D size of the widgets. The viewpoint was chosen so that all the parts of each widget and the spatial relations between these parts were clearly visible (for a similar procedure, see Yildirim & Jacobs, 2013).

The stimulus set is available at the following persistent URL: https://osf.io/q4p3g/ . It is organized into two folders and a .pdf file that can all be downloaded. The first folder, entitled "haptic widgets", comprises 24 files representing each object in gcode and 24 files representing each object in stl, both formats used in 3D printing. Two digits in the files label individual objects: the first digit represents the category to which the object belongs (1, 2, 3 or 4), and the second represents the object's exemplar number (1, 2, 3, 4, 5 or 6). For instance, a file entitled "Object 1-5.gcode" provides the gcode information for Exemplar 5 of Category 1. A second folder, entitled "visual widgets", comprises 24 files representing each object in .png, for paper printing. Again, individual objects are labeled by two digits in the files, as described above for the haptic version. Finally, a .pdf file offers a visual overview of the full stimulus set.

3. Study 1

In this study, we examined how young adults categorized a set of 24 3D widgets (or pictures of widgets) as quickly and accurately as possible, using either haptics or vision, in two different versions of a categorization task (free or cued). We predicted that categorization performances (accuracy and time) would be better (i.e., higher accuracy and/or shorter response time) in the visual modality than in the haptic one, and better when categorization was cued rather than free.

3.1. Method

3.1.1. Participants

A total of 60 young adults (26 men, 34 women; mean age = 20 years, age range = 18-23, *SD* = 1) took part in Study 1. Participants were university students. They mostly self-reported as right-handed (*n* = 52), and had no known tactile or visual impairment. Informed written consent was obtained from all participants prior to their enrollment in the study. The study was conducted in accordance with the Declaration of Helsinki.

3.1.2. Design

We used a 2 x 2 between-participants design, with sensory modality (haptic vs. visual) and categorization task (free vs. cued) as the main independent variables. Participants were randomly assigned to one of the four resulting conditions, with 15 participants per condition: free haptic categorization, cued haptic categorization, free visual categorization, and cued visual categorization.

3.1.3. Material and Procedure

The material consisted of 24 widgets and their corresponding gray-scale pictures. Individual sessions took place in a quiet room at the university, which was equipped with video cameras. Participants sat at a table with the experimenter. In the haptic modality, the full set of 24 widgets was randomly placed on the table form a compact circular whole. To control for priming effects and location confounds, stimulus locations were randomized per participant. For each participant, and before the experimental session started, the experimenter proceeded by hand to a random selection of the stimuli (these were put in an opaque bag) and posited them randomly one by one on the table so as to form a compact circle in the end. The participants were blindfolded during the haptic categorization tasks (they wore a sleeping mask), and were allowed to manually explore the stimuli as they wished. There were no restrictions, and participants could use both hands. In the visual modality, the full set of 24 gray-scale pictures of widgets was randomly placed on the table in a compact circle. Participants could see the pictures and were allowed to handle them as they wished. Note that our task was not truly a visual task, but a visuo-motor one with additional haptic input (participants manipulated the pictures by hand). Reliance on hand manipulation, which was inherently present in the haptic task, was voluntarily introduced in the visual task so that potential behavioral confounds relative to praxis abilities applied similarly to both tasks.

In Condition 1 (free haptic categorization), the experimenter gave the following verbal instruction: “On this table, there are 24 objects that you can only explore by touch. You are free to use both hands. The task requires you to group the objects that look alike, that is to say, according to their resemblance. You need to perform this task as precisely as possible, but also as quickly as possible. OK? When I say ‘go’, you can start.” In this condition, no specific information was given to participants regarding how to group the objects, except on the basis of their perceived similarities. Note that 'resemblance' (used in our verbal instruction) is not proper to the visual domain, but also applies to the tactile, auditory or olfactory domains; 'Precisely' equals "accurately", meaning that there was a correct manner to categorize the set of stimuli. In fact, the inherent characteristics of our stimuli made that participants had to work on a type of resemblance that focused only on formal properties of objects (namely their shape), since widgets did not vary on material dimensions (such as texture, weight or temperature) that could have been potentially used to establish tactile resemblance between stimuli. In Condition 2 (cued haptic categorization), the procedure was the same as in Condition 1, except that the task instruction included the following additional information: “You should know that there are four different groups, each comprising six exemplars”. In this condition, participants were cued regarding how to group the objects together, in terms of the number and size of the groups, before they started the categorization task (see also Gaissert et al., 2011). Conditions 3 (free visual categorization) and 4 (cued visual categorization) were similar to Conditions 1 and 2, respectively, except that the material comprised pictures of the widgets, and the sorting task was performed in the visual modality, meaning that the participants had their eyes open during the entire session. Participants in each condition performed the categorization task once only.

Immediately after performing the categorization task, participants were asked to respond verbally to a series of four questions: “Could you explain why you put these objects/pictures together in a same group?”; “Did the objects/pictures make you think of something you knew?”; and “On a 10-point scale ranging from 1 (*Very low*) to 10 (*Very high*), how would you rate the stress of performing the categorization task?”; and “On a 10-point scale ranging from 1 (*Very low*) to 10 (*Very high*), how would you rate the difficulty of the categorization task?”. It should be noted that participants in the haptic modality remained blindfolded at this point. Afterwards, participants were thanked for their participation in the study. Those who had performed it in the haptic modality took their blindfolds off and were allowed to see the 3D objects.

For each participant, the experimenter recorded the time required to perform the categorization task, the number of groups formed, the identity of the objects in each group, and the verbal responses given to the questions posed by the experimenter. Individual video recordings were used for this purpose.

3.2. Results

Owing to the small sample size for each condition ($n = 15$), we ran nonparametric tests (Kruskal-Wallis and Dunn). We set the alpha level at 0.05 for all statistical analyses.

3.2.1. Time taken to perform the categorization task

We measured the time that elapsed between the experimenter saying “go” and the participant declaring that he or she had finished the categorization task. Individual times were averaged across participants in each condition. The mean categorization times per condition are provided in Table 4.

Results (see Table 4) showed that it took participants about 10 minutes to perform the categorization task in the haptic modality. By contrast, and as expected, they were faster in the visual modality, categorizing the pictures within about 3 minutes on average. Contrary to expectations, there was no specific advantage of the cued conditions over the free conditions in terms of mean categorization times, whichever sensory modality was involved. Specifically, participants were no quicker when they were informed about the number and size of groups to be formed. A Kruskal-Wallis test run to determine whether mean completion times varied significantly across conditions confirmed that this was the case ($H = 40.84$, $p = 0.001$). Dunn's multiple pairwise comparisons were run to pinpoint the significant differences. These indicated that times differed significantly between the haptic and visual modalities (all *p*s < 0.05), but not between the free and cued versions of the task in a given sensory modality (all *p*s *ns*). Thus, the significant factor for variations in categorization times was sensory modality, with vision leading to shorter categorization times than haptics.

-Insert Table 4 about here-

3.2.2. Accuracy of categorization

For each participant, we created a matrix featuring all 24 objects in rows and columns, and indicated which objects had been grouped together (see Appendix A for an example). Comparisons between this matrix and the ideal one (i.e., the one that was expected in the case of perfect categorization) enabled us to determine the number of concordant (max. 60) and discordant cells (max. 216). The percentage of correct pairings of objects was calculated as the number of concordant cells divided by 60 (maximum number of possibly concordant cells) and multiplied by 100. The percentage of incorrect pairings of objects was calculated as the number of discordant cells divided by 216 (maximum number of possibly discordant cells) and multiplied by 100. For each participant, a final categorization score was calculated as the percentage of correct pairings of objects minus the percentage of incorrect pairings of objects. Individual scores were then averaged across participants within each condition. The mean categorization scores per condition are provided in Table 4.

Results (see Table 4) showed that participants were very accurate[3] in categorizing the material when they were informed about the number and size of the groups they had to construct (93.46% and 94.89% accuracy in the two cued conditions). It should be noted that 11 of the 15 participants in the cued haptic condition performed at ceiling level (i.e., 100% accuracy), and 13 of the 15 participants in the cued visual condition performed at ceiling level. By contrast, and as expected, participants performed more poorly when they had no information (40.49% and 45.28% accuracy in the two free conditions). Contrary to expectations, there was no specific advantage of using vision rather than active touch to perform the categorization tasks. Surprisingly, participants were no more accurate in the visual modality than they were in the haptic one. A Kruskal-Wallis test indicated that mean categorization scores varied significantly across conditions (H = 4.15, p = 0.001). Dunn comparisons indicated that accuracy differed significantly between the free and cued categorization conditions (all ps < 0.05), but not between the two sensory modalities (all ps *ns*). Thus, the significant factor for variation in performance accuracy was categorization condition, with cued categorization leading to higher accuracy compared with free categorization.

3.2.3. Number of groups

The number of groups established by participants varied between two and 12. Participants in the cued conditions complied with the verbal instructions given by the experimenter and produced four groups, as requested (see results in Table 4). By contrast, participants in the free conditions produced more groups than necessary, with an average of six groups in the haptic modality and eight groups in the visual modality. A Kruskal-Wallis test indicated significant differences in the numbers of groups produced across conditions, H = 32.33, p = 0.001. Dunn comparisons revealed significant differences between the free and

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[3] Categorization scores were all above chance level (which was 0.000000001% in Study 1).

cued tasks within each modality (all *p*s < 0.05), but not between the haptic and visual modalities for the free categorization conditions (*p ns*). Thus, participants in the free exploration conditions overestimated the number of groups to be produced, whereas those in the cued conditions strictly complied with the requested number of groups.

3.2.4. Perceived stress and difficulty

Participants' subjective ratings of the stress they experienced while performing the task were generally moderate in all conditions, except for the free haptic condition, where they were quite low (see results in Table 4). A Kruskal-Wallis test indicated that mean perceived stress varied significantly across conditions ($H = 8.61$, $p = 0.03$), but the only significant difference was between Conditions 1 and 3 (Dunn test, $p = 0.05$). Difficulty was also rated as generally moderate across all conditions (see results in Table 4). The mean values for difficulty did not differ significantly across conditions (Kruskal-Wallis test, $H = 1.25$, $p = 0.73$). Thus, subjectively perceived stress was lower in the free haptic condition than in the free visual condition, and perceived difficulty was moderate whatever the condition.

3.2.5. Verbal comments on widgets

When asked whether the stimuli made them think of something they knew (Question 2, Method section), participants provided three types of answers: nothing (i.e., widgets did not resemble anything they knew); animals (i.e., widgets resembled animals such as turtles, dinosaurs, fish, or mice); or objects (i.e., widgets looked or felt like objects such as UFOs, spaceships, space modules, or the Teletubbies' house from the preschoolers' TV series). Table 4 shows how responses were distributed across these three types in the haptic and visual modalities. A chi^2 test revealed that the distribution of responses varied across modalities, $\chi^2 = 6.83$, $p = 0.03$. As the results showed (see Table 5), more participants provided *animal* answers in the haptic modality than in the visual one.

-Insert Table 5 about here-

3.2.6. Declared processed features

We assessed which object properties participants mentioned when asked to explain why they put objects/pictures together in the same group (Question 1, Method section). Participants could refer to four relevant features, namely *eyes, tail, crest,* and/or *legs*. We further distinguished between references to the *shape* and *position* of these features. It should be recalled that both the shape and the position of the features were relevant criteria for defining objects within a given category (see Stimulus characteristics section). We awarded 1 point whenever a participant mentioned a criterion. For example, the response “I put these objects together because they all had a round tail”, was awarded 1 point for tail and 1 point for shape, while “In this group, the tops of the objects (crest) had the same shape but some faced different ways”, was awarded 1 point for crest, 1 point for shape, and 1 point for position). Finally, we counted the maximum number of features a participant mentioned when describing a given group (range: 1-4).

-Insert Fig. 2 about here-

Figure 2 shows the frequency with which participants mentioned relevant object features and referred to shape and position when explaining how they performed the categorization task in the haptic or visual modality. The frequency with which participants mentioned object features varied according to modality. In the haptic modality, participants mostly mentioned the objects’ tail and crest, whereas they mostly referred to the crest and legs in the visual modality. Figure 2 also shows that whereas participants systematically referred to the shape of the elements, they less often referred to their position, whatever the categorization condition. Finally, none of the participants simultaneously mentioned all four relevant features when describing the objects’ perceptual similarities. The maximum mean number of features mentioned by participants when describing a given group was 1.20 (*SD* = 0.41) in the free haptic condition, 1.53 (*SD* = 0.64) in the cued haptic condition, 1.79 (*SD* =

0.80) in the free visual condition, and 1.62 (*SD* = 0.65) in the cued visual condition. These means did not differ with condition (Kruskal-Wallis test, $H = 5.75$, $p = 0.12$).

4. Study 2

In Study 2, we assessed the accuracy of younger participants (i.e., children and adolescents) in categorizing a set of 16 3D widgets (or pictures of widgets) in the haptic and visual modalities. Participants had to categorize the stimuli first in one modality, then the other (order controlled), and were told how many groups (and how many exemplars per group) they had to produce (cued categorization). We predicted that categorization accuracy would be higher in the visual modality than in the haptic one, and examined whether any modality order effects occurred. Based on previous studies in the field of cross-modal transfer of spatial properties of objects between vision and touch (see Hatwell et al., 2003; Heller & Gentaz, 2014, for reviews), we anticipated that modality order effects, if present, would lead to higher categorization accuracy in the haptic-to-vision direction (than in the vision-to-haptic).

4.1. Method

4.1.1. Participants

Participants were 40 children and adolescents, divided into two age groups: children (n = 20; mean age = 7.75 years, age range = 7.16-7-41, *SD* = .41; 11 girls and 9 boys), and adolescents (n = 20; mean age = 14.75 years, age range = 14-15.66, *SD* = .41; 13 girls and 7 boys). Informed written consent was obtained from their parents prior to their enrollment in the study. The study was conducted in accordance with the Declaration of Helsinki.

4.1.2. Design

We used a mixed factorial design with sensory modality (2: haptics vs. vision) as a within-participants factor, and age group (2: children vs. adolescents) and order (2: haptic then visual vs. visual then haptic) as between-participants factors.

4.1.3. Material and Procedure

The material consisted of 16 widgets that were randomly selected from the full set of stimuli (Objects 1.1, 1.2., 1.4., 1.5; Objects 2.1, 2.2., 2.4., 2.5; Objects 3.1, 3.2., 3.4., 3.5; and Objects 4.1, 4.2., 4.4., 4.5; see Fig. 1- leftmost columns), and their corresponding gray-scale pictures. Pretests (which were additional pretests conducted prior to the studies) had revealed that children were uncomfortable exploring 24 objects in the haptic modality. More precisely, five children and five adolescents of the same age range that the participants of study 2 were invited to perform the categorization tasks, and were debriefed afterwards. It came out from the pretests that the young participants did not report difficulty in understanding the verbal instructions used in the tasks. Notably, the verb 'resemble' (which age of acquisition is usually around 10 years; Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012) was well understood in the context of the given instruction. Verbal comments provided by the young participants however revealed a discomfort due to the large quantity of stimuli to be processed in the haptic as well as in the visual tasks. We therefore restricted the size of our stimulus set to 16 objects (4 exemplars x 4 categories), in order to made the categorization task feasible for our young participants. For this specific subset of widgets, the number of primitives shared by objects within each category was either 0 or 2 (see Table 3 for details).

Individual sessions took place in a quiet room at the children’s primary school or adolescents’ high school. Participants had to perform the categorization task twice: once in the haptic modality, and once in the visual modality. The order of the modalities was counterbalanced within each age group (i.e., half the participants in each age group started in the haptic modality and then continued in the visual modality, and the other half started in the visual modality and then continued in the haptic modality[4]). There were no practice trials beforehand.

For the categorization task in the haptic modality, 16 widgets were randomly placed on a table to form a compact circular whole. Participants wore a sleeping mask, but could freely handle the stimuli. The verbal instruction was as follows: “There are 16 objects front of you, on this table, that you are free to handle as you want. You must group objects that go well together and resemble each other. You must make four different groups, with four objects in each group. OK? When I say ‘Go’, you can start”. In the visual task, 16 gray-scale pictures of widgets were randomly placed on the table to form a compact circular whole. Participants could see the pictures and were free to handle them as they wished. The verbal instruction was as follows: “There are 16 pictures of objects in front of you, on this table, that you are free to handle as you want. You must group pictures of objects that go well together and resemble each other. You must make four different groups, with four objects in each group. OK? When I say ‘Go’, you can start”. It should be noted that, in contrast to Study 1, we only used cued conditions of categorization (and not free ones), and did not impose any time constraints, in order to adapt the task to our sample of participants. Pretests had indicated that younger participants were disturbed the lack of information regarding the number of groups to be produced, and by the use of a time constraint.

4.2. Results

The main dependent variable was categorization accuracy, measured using the same method as that described in Study 1 (accuracy = percentage of matching pairs minus percentage of nonmatching pairs; individual matrices were created on the basis of 16 objects, with a maximum number of 24 concordant cells and 96 discordant cells). As before, owing to

[4] Participants in each age group were randomly assigned to the Visual-Haptic (VH) or Haptic-Visual (HV) order. There were no significant variations in chronological age between participants assigned to order HV and those assigned to order VH, whatever the age group.

the small sample sizes, we used nonparametric tests (Mann-Whitney *U* test for independent series, and Wilcoxon test for paired series), with an alpha level of 0.05. Table 6 summarizes the main findings.

-Insert Table 6 about here-

Results (see Table 6) indicated that haptic performances were slightly poorer than visual performances, whatever the age group. However, the differences between the two sensory modalities did not reach significance, whether we considered data for the children (Wilcoxon test, $p = 0.09$) or for the adolescents (Wilcoxon test, $p = 0.19$). Thus, contrary to our expectation, we did not find any evidence of a significant effect of sensory modality on categorization accuracy[5]. It should be noted that overall performance was good, but did not reach ceiling level. A closer look at the data showed that only nine children and nine adolescents out of the 40 participants performed at ceiling level (i.e., 100% accuracy) in the haptic modality, and 13 children and 11 adolescents performed at ceiling level in the visual modality. In both the children and adolescents, accuracy levels in the haptic and visual modalities were significantly correlated, as attested by Spearman's rank correlation coefficient (children: rho = 0.47, $p = 0.03$; adolescents: rho = 0.54, $p = 0.01$).

Regarding possible order effects, Mann-Whitney *U* tests revealed that there were no significant order effects on children's haptic and visual performances (all *p*s > 0.28). In adolescents, Mann-Whitney *U* tests indicated that haptic performances did not vary significantly with order ($p = 0.18$), but visual performances did, being higher when the haptic modality preceded the visual one (mean = 95.83%) than the reverse (65.62%; Mann-Whitney *U* test: $p = 0.04$). Thus, adolescents scored higher on the task in the visual modality when they had already performed it in the haptic modality. Finally, a comparison between children's and

[5] Categorization scores were all above chance level (which was 0.00003% in study 2).

adolescents' performances indicated no difference across age groups according to modality (Mann-Whitney *U* tests, all *p*s > 0.31).

5. Discussion

In the present work, we developed a new set of parametrically defined objects, called *widgets*, for use as 3D (or 2D) materials for haptic (or visual) categorization purposes. We also assessed and demonstrated the validity of this stimulus set by conducting two separate studies of haptic and visual categorization, involving participants of different ages: young adults in Study 1, and children and adolescents in Study 2. We summarize and discuss our main findings below.

5.1. Categorizing complex 3D shapes was possible in both modalities (haptic/visual)

We found that humans can categorize complex 3D shapes on the basis of haptically or visually perceived similarities in shape attributes. Because our stimuli only differed on shape properties, participants in both studies had to find similarities (and dissimilarities) in shape between the objects in order to classify them. Similarity between objects is an important factor that is known to influence categorization (Goldstone, 1994). In Study 1, our adult participants exhibited high performance accuracy (40-95%), which crucially did not differ significantly across the haptic and visual modalities. In Study 2, we obtained a similar finding, with children and adolescents performing well (64-96%) on the categorization task (cued version), again with no significant difference in performance accuracy across modalities. The finding that our participants (adults, children or adolescents) were just as accurate in the haptic modality as they were in the visual modality is surprising, considering that they did not receive any haptic training with the objects or categories before they performed the categorization task. In particular, their good level of performance contrasts sharply with recognition performances for raised-line 2D drawings, which is usually poor in the haptic modality (Lebaz, Jouffrais, & Picard, 2012; Lederman, Klatzky, Chataway, & Summers, 1990; Picard & Lebaz, 2012). In our studies, touch was used in the apprehension of 3D shapes, whereas in a 2D drawing recognition task it is necessary to go through an "image-mediation" process (Lederman et al., 1990), which may be far more complex and explain lower levels of accuracy.

5.2. Categorizing complex 3D shapes was easier when cues were given

As expected, the adult participants performed better in the cued (vs. free) categorization conditions in Study 1. More specifically, in the cued conditions, they created the requested number of groups, and displayed very high categorization accuracy on average (94%). By comparison, in the free conditions, participants overestimated the number of groups they needed to create, leading them to make more categorization errors. As a result, they performed lower on average (42%). This finding can be explained by the positive influence of top-down processes when participants were given information about how to categorize the objects (number and size of groups). Moreover, providing this information reduced the degree of freedom associate with the task, thereby facilitating its performance. The advantageous effect of cuing a categorization task is also consistent with the findings of Gaissert et al. (2011), who reported that more condensed clusters were generated in the perceptual spaces when participants received instructions about how to categorize objects.

5.3. Categorization speed differed across modalities (but not across conditions)

In Study 1, we found that our adult participants performed the categorization task somewhat more slowly in the haptic modality than in the visual one. This difference in categorization speed between vision and touch is not surprising, and probably reflects the slow and sequential extraction of information about object properties through exploratory hand movements in the haptic modality, contrasting with the fast and parallel processing of information in the visual modality (Hatwell, Streri, & Gentaz, 2003). To take this difference into account, previous visuohaptic studies usually allowed more time for haptic versus visual exploration, using a 2:1 (haptic:visual) ratio to avoid placing haptics at a disadvantage (e.g., Gaissert et al., 2011; Haag, 2011; Lacey, Pappas, Kreps, Lee, & Sathian, 2009; Newell, Ernst, Tjan, & Bulthoff, 2001).

By contrast, in Study 1, there was no difference in categorization time between free and cued conditions. It is noteworthy that in both conditions participants received all objects on a table and first scanned them (either visually, or with their hands) before starting the categorization procedure. It is likely that this initial scanning has served as prior learning or familiarization with the material, which could partly explain the lack of time difference between constrained and unconstrained categorization.

5.4. Object properties were differently weighted across modalities

Our finding of comparable performance accuracy across the visual and haptic modalities suggests that vision and haptics are very similar in terms of categorization mechanisms. There were, however, slight differences in the ways the objects were haptically and visually categorized, as their properties were differentially weighted across the modalities. In Study 1, we found that adult participants mostly mentioned the objects' tail and crest in the haptic modality, whereas in the visual modality, they mostly referred to the crest and legs. This difference can be explained by the relative salience of each feature. In the haptic modality, the crest was usually the first tactile feature felt by the hand when a participant grasped the object. The tail was also very salient during tactile exploration, being more prominent than the legs and eyes, and participants often held the widgets by the tail when handling them. In the visual modality, the three quarters view of the objects meant that the features at the front (legs, crest) were more salient than the feature at the back (tail). Although the eyes were at the front, because they were smaller than the legs or the crest, they may have been less visually salient, and were therefore mentioned less. Differences in perceptual salience between vision and touch are a well-known phenomenon in the field of haptic research (see, for example, Klatzky, Lederman, & Reed, 1987), and have already been illustrated in several studies of haptic categorization. For instance, in Gaissert et al.'s study (2011), the three shape dimensions of the stimuli (shell-shaped objects) were weighted differently in each modality: symmetry was more important than convolutions for vision, whereas the reverse was true for haptics, and the aperture-tip distance was the least important factor for both modalities. Using 3D spheres that varied on both shape and texture attributes, Cooke et al. (2007) also found that these two dimensions were weighted differently according to sensory modality: shape was more important than texture for visual categorization, whereas shape and texture were more or less equally weighted in the haptic and visuohaptic conditions.

5.5. Participants had a limited ability to verbalize object properties

Possibly the most surprising finding of our study was the sharp contrast between the participants' very good level of performance and their very poor ability to explain in their own words how they performed the categorization, that is to say, which object properties they relied on to divide the objects into groups (Study 1). First, none of the adult participants mentioned all four relevant features when describing perceptual similarities between the objects. Indeed, participants generally only mentioned two features (tail and crest in the haptic modality, and crest and legs in the visual one). Second, whereas they systematically referred to the shape of the features, they less often referred to their position. Taken together, these findings suggest that our stimuli were highly complex to describe, even for young adults. The widget production rules were obviously not transparent to them, even when their eyes were open. The adult participants only considered (or only verbalized) a very small proportion of the complex parameters that defined the within-category similarities and between-category differences of our stimulus set. Our free verbalization method may not have been adequate, and alternative methods, such as the use of more structured questionnaires, might have been more efficient at eliciting information. It may also be that, regardless of the limitations of our chosen method, participants had no explicit (conscious) access to the complex parameters that defined our stimulus set. In future studies, it would be worth investigating the content of the internal representations of the stimuli constructed by participants who successfully perform the categorization task. One key question for research is how far this content can be made explicit (conscious, and accessible to verbal language).

5.6. Modality order had an effect on categorization accuracy (in adolescents)

We found a modality order effect in Study 2, where we used sensory modality as a within-participants factor. More specifically, we found that adolescents scored higher on the task in the visual modality when they had already performed it in the haptic modality. This finding may suggest that adolescents benefited from prior haptic categorization of the stimuli. This finding is in line with our hypothesis, and previous studies that have reported asymmetrical transfer performances in children and adults, with better performances from touch to vision than from vision to touch when spatial properties of objects are involved (see for reviews: Hatwell et al., 2003; Heller & Gentaz, 2014). Other studies have reported cases where haptic information dominated vision as well as the reverse in children (5-10 years) who performed size discrimination and orientation discrimination tasks, respectively (Gori, Del Viva, Sandini, & Burr, 2008). Gori et al. reported that either vision or touch dominated in children below age 8, even in conditions in which both senses should be weighted equally or in which the dominant sense was far less precise than the other, meaning that young children did not integrate yet visual and haptic form information in an optimal way.

5.7. There was no evidence of an age effect on categorization

We found no evidence that age influenced performance in Study 2, where we compared two age groups (children vs. adolescents). However, although haptic categorization proved possible not only for adults (Study 1), but also for both children and adolescents (Study 2), without any prior training with the objects, the children's and adolescents' cued categorization performances did not reach ceiling level, in contrast to the adults' performances. Even though we could not directly compare the levels of accuracy across the two studies (which differed in their methods), this observation is worth noting, as it suggests that research is needed on the development of haptic categorization abilities. Previous studies have tracked the development of haptic processing abilities in children, adolescents and young adults with 2D materials (Mazella, Albaret, & Picard, 2017), and future studies could track the development of haptic processing abilities with complex unfamiliar 3D shapes. It would be interesting to relate aspects of this development to changes and improvements in memory capacity, mental imagery, and exploratory hand movements between childhood and adulthood.

5.8. Possible concrete use of widgets

To conclude, our work has implications for practice in the field of psychology and visual impairment that severely lacks suitable testing devices to assess cognitive and perceptual skills without vision. Our new set of parametrically defined objects can be used to fill an important lack of adapted tools in this field. Our material may also have a concrete use to assess perceptual skills in old people, with or without cognitive impairment. The question of how aging affects haptic (compared to visual) perception, recognition, and memory has received considerable attention in the last years (see e.g., Dowell et al., 2018; Ferreira et al., 2019; Godde et al., 2018; Norman et al., 2015; Skedung et al., 2018). Indeed, despite decline in tactile sensitivity with aging (Skedung et al., 2018), recent findings showed a variety of preserved abilities in older adults: for instance, preserved haptic shape recognition abilities (compared to visual shape recognition abilities; Norman et al., 2015), preserved adaptation to the visual–haptic size conflict (compared to younger adults; Couth, Gowen, & Poliakoff, 2018), or preserved interhemispheric tactile communication (relative to younger adults; Dowell, et al., 2018). Widgets can be used as controlled materials to test how haptic and/or visual perceptual skills preserve or deteriorate in older people.

6. References

Ashby, F. G., & Maddox, W. T. (2005). Human category learning. *Annual Review of Psychology*, *56*, 149-178. DOI:10.1146/annurev.psych.56.091103.070217

Cooke, T., Jäkel, F., Wallraven, C., & Bülthoff, H. H. (2007). Multimodal similarity and categorization of novel, three-dimensional objects. *Neuropsychologica*, *45*, 484-495. https://doi.org/10.1016/j.neuropsychologia.2006.02.009

Couth, S., Gowen, E., & Poliakoff, E. (2018). How does ageing affect grasp adaptation to a visual-haptic size conflict?. *Experimental brain research*, *236*, 2173–2184. https://doi.org/10.1007/s00221-018-5288-1

Dowell, C. J., Norman, J.F., Moment, J. R., Shain, L. M., Norman, H. F., Philips, F., & Kappers, A. M. L. (2018). Haptic shape discrimination and interhemispheric communication. Scientific Reports, 8, 377. DOI:10.1038/s41598-017-18691-2

Edelman, S. (1998). Representation is representation of similarities. *The Behavioral and Brain Sciences*, *21*, 449-498. https://doi.org/10.1017/S0140525X98001253

Ferreira, C. D., Gadelha, M. J. N., Fonseca, E. K. G. D., Silva, J. S. C. D., Torro, N., & Fernadez-Calvo, B. (2019). Long-term memory of haptic and visual information in older adults. *Neuropsychology, Development, and Cognition, 31*, 1-13. DOI:10.1080/13825585.2019.1710450.

Gaissert, N., Bülthoff, H. H., & Wallraven, C. (2011). Similarity and categorization: From vision to touch. *Acta Psychologica*, *138*, 219-230. DOI: 10.1016/j.actpsy.2011.06.007

Gilson, E. Q., & Baddeley, A. D. (1969). Tactile short-term memory. *Quarterly Journal of Experimental Psychology*, *21*, 180-184. https://doi.org/10.1080/14640746908400211

Godde, B., Bruns, P., Wendel, V., & Trautmann, M. (2018). Effects of age and individual experiences on tactile perception over the life span in women. Acta Psychologica, 190, 135-141. https://doi.org/10.1016/j.actpsy.2018.08.004

Goldstone, R. L. (1994). The role of similarity in categorization–providing a groundwork. *Cognition*, *52*, 125-157. DOI:10.1016/0010-0277(94)90065-5

Gori, M., Del Viva, M., Sandini, G., & Burr, D. (2008). Young children do not integrate visual and haptic form information. *Current Biology, 18*, 694-698. https://doi.org/10.1016/j.cub.2008.04.036

Haag, S. (2011). Effects of vision and haptics on categorizing common objects. *Cognitive Processing*, *12*, 33-39. DOI: 10.1007/s10339-010-0369-5

Hatwell, Y., Streri, A., & Gentaz, E. (2003). *Touching for knowing*. Amsterdam/Philadelphia, PA: John Benjamins.

Heller, M. A., & Gentaz, E. (2014). *Psychology of touch and blindness*. New York: Psychology Press.

Homa, D. (1984). On the nature of categories. *Psychology of Learning and Motivation*, *18*, 49–94. https://doi.org/10.1016/S0079-7421(08)60359-X

Homa, D., Kahol, K., Tripathi, P., Bratton, L., & Panchanathan, S. (2009). Haptic concepts in the blind. *Attention, Perception, & Psychophysics*, *71*(4), 690-698. https://doi.org/10.3758/APP.71.4.690

James, T.W., Shima, D.W., Tarr, M.J., & Gauthier, I. (2005). Generating complex three-dimensional stimuli (Greebles) for haptic expertise training. *Behavior Research Methods*, *37*, 353-358. https://doi.org/10.3758/BF03192703

Klatzky, R. L., Lederman, S. J., & Metzger, V. A. (1985). Identifying objects by touch: An “expert system”. *Perception & Psychophysics*, *37*, 299-302. https://doi.org/10.3758/BF03211351

Klatzky, R. L., Lederman, S. J., & Reed, C. L. (1987). There's more to touch than meets the eye: The salience of object attributes for haptics with and without vision. *Journal of Experimental Psychology: General*, *116*, 356-369. DOI 10.1037/0096-3445.116.4.356

Kuperman, V., Stadthagen-Gonzalez, H., & Brysbaert, M. (2012). Age-of-acquisition ratings for 30,000 English words. *Behavior Research Methods, 44*, 978-90. https://doi.org/10.3758/s13428-012-0210-4.

Lacey, S., Pappas, M., Kreps, A., Lee, K., & Sathian, K. (2009). Perceptual learning of view-independence in visuo-haptic object representations. *Experimental Brain Research*, *198,* 329-337. doi: 10.1007/s00221-009-1856-8.

Lacey, S., Peters, A., & Sathian, K. (2007). Cross-modal object recognition is view-point dependent. *PloS ONE, 2(9),* e890. https://doi.org/10.1371/journal.pone.0000890.

Lebaz, S., Jouffrais, C., & Picard, D. (2012). Haptic identification of raised-line drawings: High visuospatial imagers outperform low visuospatial imagers. *Psychological Research*, *76*(5), 667-675. https://doi.org/10.1007/s00426-011-0351-6.

Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology, 19*, 342-368. https://doi.org/10.1016/0010-0285(87)90008-9.

Lederman, S. J., & Klatzky, R. L. (1990). Haptic classification of common objects: Knowledge-driven exploration. *Cognitive Psychology*, *22*, 421-459. https://doi.org/10.1016/0010-0285(90)90009-S.

Lederman, S. J., Klatzky, R. L., Chataway, C., & Summers, C. D. (1990). Visual mediation and the haptic recognition of two-dimensional pictures of common objects. *Perception & Psychophysics*, *47*, 54-64. https://doi.org/10.3758/BF03208164.

Lederman, S.J., & Klatzky, R.L. (2009). Haptic perception: A tutorial. *Attention, Perception, & Psychophysics*, *71,* 1439–1459. https://doi.org/10.3758/APP.71.7.1439.

Mazella, A., Albaret, J.-M., & Picard, D. (2017). The development of haptic processing skills from childhood to adulthood by means of two-dimensional materials. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, *72*(1), 48–57. https://doi.org/10.1037/cep0000121.

Medin, D. L., & Schaffer, M. M. (1978). Context theory of classification learning. *Psychological Review*, *85*, 207–238. https://doi.org/10.1037/0033-295X.85.3.207.

Milton, F., & Wills, A. (2004). The influence of stimulus properties on category construction. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *30*, 407-415. https://doi.org/10.1037/0278-7393.30.2.407.

Newell, F. N., Ernst, M. O., Tjan, B. S., & Bulthoff, H. H. (2001). Viewpoint dependence in visual and haptic object recognition. *Psychological Science*, *12*, 37-42. https://doi.org/10.1111/1467-9280.00307.

Norman, F.J., Norman, H.F., Clayton, A.M., Lianekhammy, J., & Zielke, G. (2004). The visual and haptic perception of natural object shape. *Perception & Psychophysics*, *66*, 342-351. https://doi.org/10.3758/BF03194883.

Norman, J. F., Cheeseman, J. R., Adkins, O. C., Cox, A. G., Rogers, C. E., Dowell, C. J., Baxter, M. W., Norman, H. F., & Reyes, C. M. (2015). Aging and solid shape recognition: Vision and haptics. *Vision Research*, *115*, 113-118. https://doi.org/10.1016/j.visres.2015.09.001

Nosofsky, R. M. (1992). Exemplar-based approach to relating categorization, identification, and recognition. In F. G. Ashby (Ed.), *Scientific psychology series. Multidimensional models of perception and cognition* (p. 363–393). Lawrence Erlbaum Associates, Inc.

Picard, D., & Lebaz, S. (2012). Identifying raised-line drawings by touch: A hard-but not impossible-task. *Journal of Visual Impairment & Blindness*, *106*(7), 427-431. https://doi.org/10.1177/0145482X1210600705.

Picard, D., & Monnier, C. (2009). Short-term memory for spatial configurations in the tactile modality: A comparison with vision. *Memory, 17,* 789-801. DOI:10.1080/09658210903107838.

Picard, D., Dacremont, C., Valentin, D., & Giboreau, A. (2003). Perceptual dimensions of tactile textures. *Acta Psychologica*, *114*, 165-184. DOI:10.1016/j.actpsy.2003.08.001.

Posner, M. I., & Keele, S. W. (1968). On the genesis of abstract ideas. *Journal of Experimental Psychology*, *77*, 353-363. https://doi.org/10.1037/h0025953.

Rosch, E. (1978). Principles of categorization. In A. Collins & E. E. Smith (Eds.), *Readings in cognitive science, a perspective from psychology and artificial intelligence* (pp. 312-322). San Mateo, CA: Morgan Kaufmann Publishers.

Schwarzer, G., Küfer, I., & Wilkening, F. (1999). Learning categories by touch: On the development of holistic and analytic processing. *Memory & Cognition, 27*(5), 868-877. https://doi.org/10.3758/BF03198539.

Skedung, L., El Rawadi, C., Arvidsson, M., Farcet, C., Luengo, G. S., Breton, L., & Rutland, M. W. (2018). Mechanisms of tactile sensory deterioration amongst the elderly. *Scientific reports*, *8*(1), 5303. https://doi.org/10.1038/s41598-018-23688-6

Sloutsky, V.M. (2010). From perceptual categories to concepts: What develops? *Cognitive Science, 34*, 1244–1286. doi: 10.1111/j.1551-6709.2010.01129.x.

Ward, T. B., & Scott, J. (1987). Analytic and holistic modes of learning family-resemblance concepts. *Memory & Cognition*, *15*, 42-54. https://doi.org/10.3758/BF03197711.

Williams, P. (1997). Prototypes, exemplars, and object recognition. Unpublished doctoral dissertation, Yale University, New Haven, CT.

Yildirim, I., & Jacobs, R. A. (2013). Transfer of object category knowledge across visual and haptic modalities: Experimental and computational studies. *Cognition*, *126*, 135-148. doi: 10.1016/j.cognition.2012.08.005.

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Table 1

Characteristics of the Methods Described in Eight Selected Papers on Haptic Categorization or Recognition Using Novel or Unfamiliar 3D Stimuli

	Stimuli	Construction mode	Attributes on which objects varied	Object size (cm)	Tasks	Conditions	Exploration mode	Participants	Results
Selected papers									
1- Schwarzer et al. (1999)	3D wooden blocks (*N* = 16)	Handmade	- Shape - Size - Texture - Weight	L: 2.8-5.2	Category learning task	Haptic	Enclosure procedure	- Adults (*N* = 20) - Children aged 3-5 yrs (*N* = 28) - Children aged 8-9 yrs (*N* = 21)	Adults prefer shape and children texture as learning attribute
2- Norman et al. (2004)	3D bell peppers (*N* = 12)	Replicas of natural objects	Shape	8.7 diameter	Recognition task (Same-different response)	- Visual - Haptic - Visual-to-haptic - Haptic-to-visual (between-subject)	Free	Adults (*N* = 56) (14 in each of 4 conditions)	Visual recognition is slightly superior (V>H=VH=HV)
3- James et al. (2005)	3D complex shapes - Greebles (*N* = 30)	- Handmade - Computer graphics + 3D printing technology	Shape	LWD: 9.3 x 4.6 x 9.0	Recognition task with prior learning (Forced-choice response)	Haptic	Free	Adults (*N* = 2) (pilot study)	No data
4- Lacey et al. (2007)	3D wooden blocks (*N* = 48)	Handmade	Shape	H: 9.5	Recognition task with prior learning (Forced-choice response)	- Visual - Haptic - Visual-to-haptic - Haptic-to-visual (within-subject)	Free	Adults (*N* = 24)	Within-modal recognition is slightly superior (V=H>VH=HV)
5- Cooke et al. (2007)	3D spheres (*N* = 25)	Computer graphics + 3D printing technology	- Shape - Texture	LWH: 9 x 8.3 x 3.7	Categorization task with prior similarity rating	- Visual - Haptic - Visuohaptic (between-subject)	Contour following procedure	Adults (*N* = 30) (10 in each of 3 conditions)	Shape dominates texture attribute for visual categorization
6- Homa et al. (2009)	3D block patterns	Handmade	- Shape - Size	10-30 length	Category learning task	Haptic	Free	- Blind adults (*N* = 20)	Blind are faster than sighted

	(*N* = 10)		- Texture					- Sighted adults (*N* = 20)	(blindfolded) controls
7- Gaissert et al. (2011)	3D shell-shaped objects (*N* = 21)	Computer graphics + 3D printing technology	Shape	LWH: 15 x 10 x 5	Categorization task with prior similarity rating : 3 different instructions (between-subject)	- Visual - Haptic (between-subject)	Free	Adults (*N* = 60) (10 in each of 2 conditions x 3 instructions)	Visual and haptic categorization correlate highly
8- Yildirim & Jacobs (2013)	3D complex shapes – Fribbles (*N* = 40)	Computer graphics + 3D printing technology	Shape	LWH: 12 x 10 x 8	Category learning task	- Visual-to-haptic - Visual 3s-to-haptic - Haptic-to-visual (between-subject)	Free	Adults (*N* = 24) (8 in each of 3 conditions)	Category knowledge transfers cross vision and haptics

Table 2

Construction Rules for Objects Based on a Combination of Primitives

	Primitives							
Object	a1	a2	b1	b2	c1	c2	d1	d2
1	✓		✓		✓		✓	
2		✓		✓		✓		✓
3	✓		✓			✓	✓	
4		✓	✓		✓			✓
5	✓			✓		✓	✓	
6		✓		✓	✓			✓
Σ	3	3	3	3	3	3	3	3

Table 3

Number of Primitives Shared by Objects in a Given Category

Object	1	2	3	4	5	6
1	-					
2	0	-				
3	3	1	-			
4	2	2	1	-		
5	2	2	3	0	-	
6	1	3	0	3	1	-

Table 4

Summary of the Main Results of Study 1. Means (and Standard Deviations) for Each Measure According to Experimental Condition

	Conditions			
	1-Free haptic categorization	2-Cued haptic categorization	3-Free visual categorization	4-Cued visual categorization
Measures				
- Categorization time (s)	573 (367)	602 (223)	113 (59)	186 (91)
- Categorization accuracy (%)	40.49 (14.02)	93.46 (12.24)	45.28 (16.90)	94.89 (13.49)
- Number of groups	6 (2)	4 (0)	8 (2)	4 (0)
- Stress (10-point scale)	2.67 (1.99)	4.20 (2.24)	4.73 (1.98)	4.80 (2.48)
- Difficulty (10-point scale)	5.47 (1.64)	5.87 (1.77)	4.87 (2.29)	5.27 (2.15)

Table 5

Distribution of Participants' Answers to Question 2 ("Did the objects/pictures make you think of something you know?") Across Three Types (*Nothing*, *Animals*, *Objects*) in the Haptic and Visual Modalities. Percentages of Answers are Provided in Parentheses

	Haptic modality (Cond.1 + Cond.2)	Visual modality (Cond.3 + Cond.4)
Nothing	5 (17%)	10 (33%)
Animals	18 (60%)	8 (27%)
Objects	7 (23%)	12 (40%)
Total	30	30

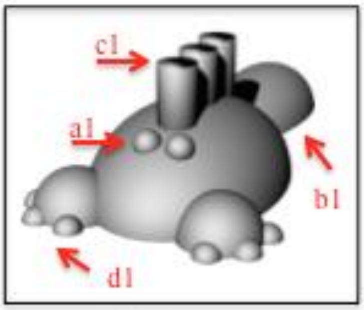
Table 6

Mean Categorization Accuracy (Standard Deviation) in the Haptic and Visual Modalities by Age Group and Order

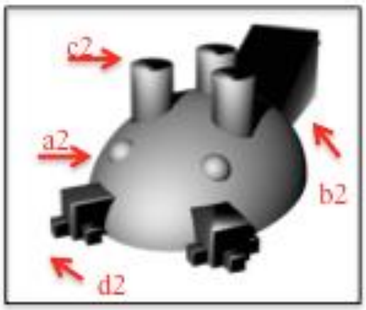
		Task	
Age group	Order	Haptic	Visual
Children	HV	69.37 (37.62)	86.35 (22.52)
	VH	64.48 (37.69)	78.23 (30.26)
	Both orders	66.93 (36.79)	82.29 (26.29)
Adolescents	HV	77.71 (26.11)	95.83 (13.18)
	VH	66.35 (30.49)	65.62 (19.67)
	Both orders	72.03 (28.29)	80.73 (22.49)

Note. Data are expressed as percentages. H = haptic; V = visual.

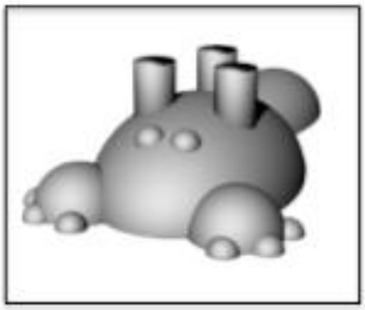
Category 1



Object 1.1



Object 1.2



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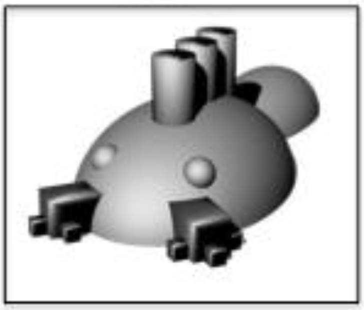
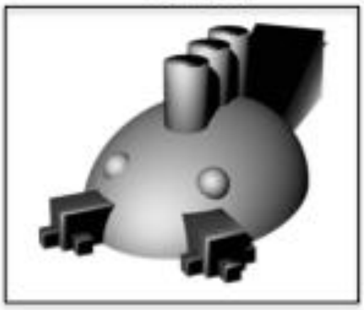


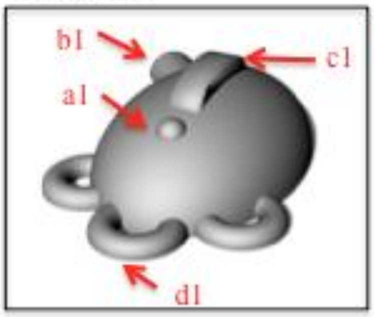
Object 1.4

Object 1.5

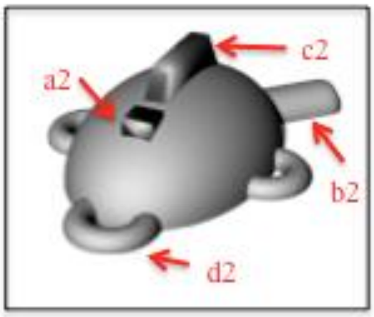


Object 1.6

Category 2



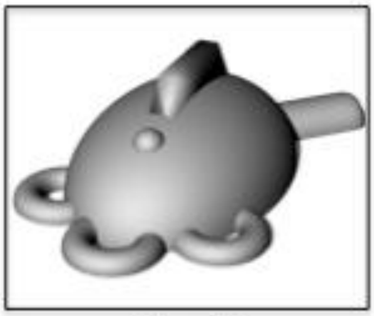
Object 2.1



Object 2.2

Object 2.3

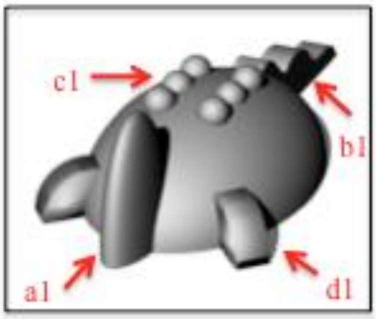
Object 2.4



Object 2.5

Object 2.6

Category 3



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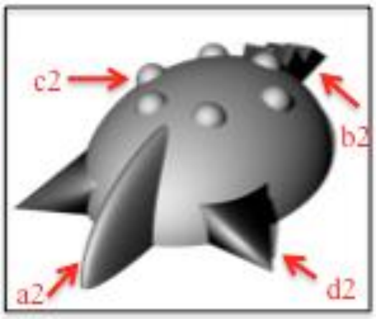


Object 3.2

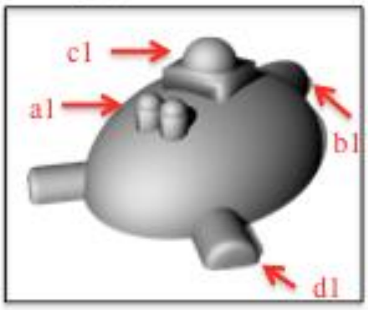
Object 3.3

Object 3.4

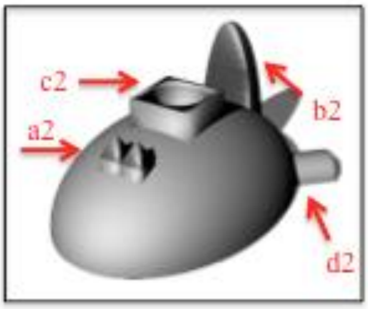
Object 3.5

Object 3.6

Category 4

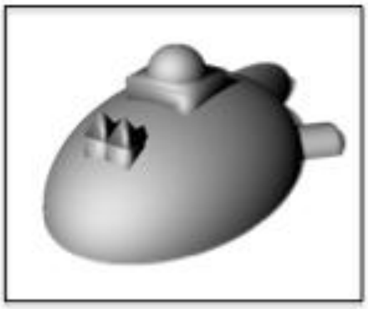


Object 4.1



Object 4.2

Object 4.3



Object 4.4

Object 4.5

Object 4.6

Figure 1

Pictures of the 24 widgets ranked by category.

The full set of 24 objects was used in study 1. Objects appearing left to the vertical dashed line were used in study 2 (16 objects).

Category 1:
a = two eyes (a1: close together; a2: far apart);
b = long tail (b1 = cylindrical; b2 = rectangular);
c = triple crest (c1: in a row; c2: as arranged in a triangle);
d = two legs with toes (d1 = round; d2 = rectangular).

Category 2:
a = single eye (a1 = round; a2 = rectangular);
b = short tail (b1 = pointing right; b2 = pointing left);
c = single crest (c1 = round; c2 = rectangular);
d = three semicircular legs (d1: close together at the front; d2 = one at the front, one on the right side, one on the left side).

Category 3:
a = large eye (a1 = vertical; a2 = horizontal);
b = long crocodile tail (b1 = curves; b2 = steps);
c = six-point crest (c1 = in two rows; c2 = arranged in a circle);
d = two front legs (d1 = rounded; d2 = triangular).

Category 4:
a = two eyes close together (a1 = rounded; a2 = triangular);
b = short tail (b1 = horizontal; b2 = vertical);
c = rectangular crest (c1 = dome on top; c2 = spherical hole inside);
d = two legs (d1 = front; d1 = back).

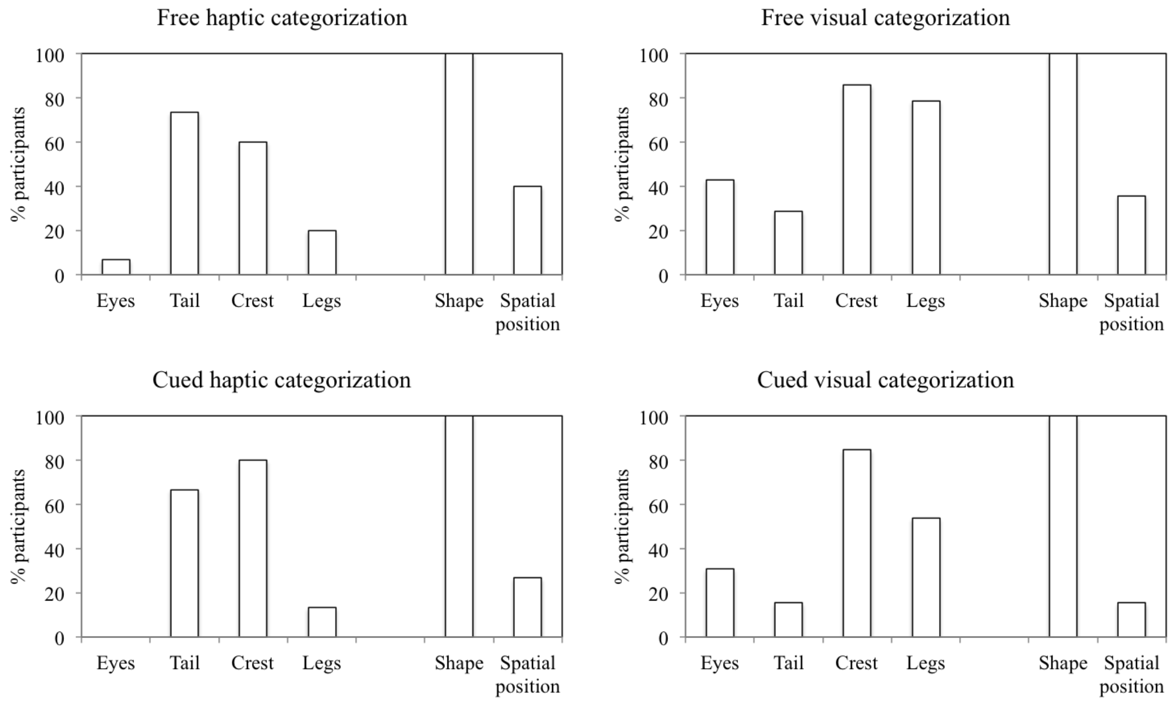


Figure 2

Verbal mention for object properties according to categorization condition.

Appendix A- Individual matrix with all 24 objects along the vertical and diagonal axes (Study 1).

Gray cells (*n* = 60) correspond to concordant pairs (filled in the case of perfect categorization). White cells (*n* = 216) correspond to discordant pairings of objects (i.e., categorization errors). In this example, a female participant in the free haptic condition produced 27 concordant and 15 discordant pairings of objects. Her haptic categorization accuracy score was therefore (27/60 * 100) - (15/216 * 100) = 45% - 6.94% = 38.06%.

	1.1	1.2	1.3	1.4	1.5	1.6	2.1	2.2	2.3	2.4	2.5	2.6	3.1	3.2	3.3	3.4	3.5	3.6	4.1	4.2	4.3	4.4	4.5	4.6
1.1	x																							
1.2		x																						
1.3	1		x																					
1.4		1		x																				
1.5		1		1	x																			
1.6	1		1			x																		
2.1							x																	
2.2								x																
2.3								1	x															
2.4							1			x														
2.5							1			1	x													
2.6												x												
3.1													x											
3.2													1	x										
3.3													1	1	x									
3.4													1	1	1	x								
3.5													1	1	1	1	x							
3.6													1	1	1	1	1	x						
4.1													1	1	1	1	1	1	x					
4.2								1	1											x				
4.3								1	1											1	x			
4.4												1										x		
4.5							1			1	1												x	
4.6												1										1		x