Our findings are rather surprising taking into account the highly unintuitive shape-parameters we altered to generate the stimulus space and also considering the fact that the participants had never explored the objects haptically before and presumably also had little experience in touching shell-shaped objects at all. Nevertheless, the haptic modality not only reconstructed the underlying stimulus dimensionality, but also was able to faithfully represent the topology of the stimuli in feature space. This result demonstrates the astonishing capabilities of the haptic modality in shape processing which are on par with those of the visual modality (Cutzu, 1998; Edelman, 1999).

Natural Sea Shells

Stimuli

The visual and the haptic perceptual spaces of shell-shaped, parametrically-defined objects are highly congruent. To see how this finding is transferrable to natural objects we gathered a set of 24 natural sea shells (Figure 4) and performed the same tasks visually and haptically as with the computer generated objects.

We chose four bivalve molluscs: *Mactra stultorum*, *Pecten maximus*, *Acanthocardia tuberculata*, and *Glycymeris insubrica*. All other objects are gastropods. Four objects have a conical shell: *Patella barbara*, *Patella longicosta*, *Patella granularis*, and *Patella vulgata*. Four shells have a turban like shell: *Turbo argyrostomus*, *Turbo coronatus*, *Turbo crassus*, and *Turbo setosus*. Four objects are extremely smooth and shiny: *Cypraea eglantine*, *Cypraea histrio*, *Cypraea lynx*, and *Ovula ovum*. Four members of the olive shells were selected: *Oliva irisans*, *Oliva miniacea*, *Agaronia gibbosa*, and *Olivancillaria vesica auricularia*. Four objects have a cone like shell: *Conus figulinus*, *Conus malacanus*, *Conus marmoreus* and *Conus textile*. Every group of four is a group of objects belonging to the same superfamily.

Similarity Ratings

The task was to rate the similarity of pairs of objects on a 7 point scale from low similarity (1) to high similarity (7). Twelve participants with normal or corrected-to-normal vision performed the visual similarity ratings. Twelve other participants were blindfolded and performed the haptic similarity ratings, palpating the objects with both hands. All participants were naïve to the stimuli and were paid 8€ per hour.

The experiment was started by introducing the objects to the participants. Every object was presented to the participants in a randomized order. In the visual modality one object was placed on a black plateau, a black curtain was automatically opened, and the participant was able to explore the object visually for 12 seconds before the curtain closed automatically. During this time the object was rotated by the experimenter to show all sides of the object. This was done as the natural objects were richer in both shape and textural features than the computer generated models. For haptic exploration the object was placed on the same plateau. A beep gave the signal to start the haptic, unrestricted exploration. 15 seconds later a second beep signalized the end of the exploration. Again, more time was given in both conditions to allow observers to sample all potentially informative stimulus properties.

In the experimental trials every object was paired once with itself and once with every other object. The pairs of objects were shown in randomized order. In contrast to the experiments using computer generated objects, here every participant had to rate every pair just once instead of three times because the previous experiments showed that the judgments did not vary over repetitions. The objects were placed on the plateau. In the visual modality the curtain was opened for 6 seconds. The object was rotated by the experimenter, who also recorded the rating of the participant. In the haptic modality, beeps signalized the beginning and the end of the exploration which lasted for 8 seconds. The exploration times were kept similar to the previous experiment to facilitate comparison.

Figure 4 Natural Sea Shells Gastropods: 1: *Patella barbara*, 2: *Patella longicosta*, 3: *Patella granularis*, 4: *Patella vulgata*. 5: *Turbo argyrostomus*, 6: *Turbo coronatus*, 7: *Turbo crassus*, 8: *Turbo setosus*. 9: *Cypraea eglantine*, 10: *Cypraea histrio, 11: Cypraea lynx*, 12: *Ovula ovum*. 13: *Oliva irisans*, 14: *Oliva miniacea*, 15: *Agaronia gibbosa*, 16: *Olivancillaria vesica auricularia*. 17: *Conus figulinus*, 18: *Conus malacanus*, 19: *Conus marmoreus*, 20: *Conus textile*. Bivalves: 21: *Mactra stultorum*, 22: *Pecten maximus*, 23: *Acanthocardia tuberculata*, 24: *Glycymeris insubrica*.

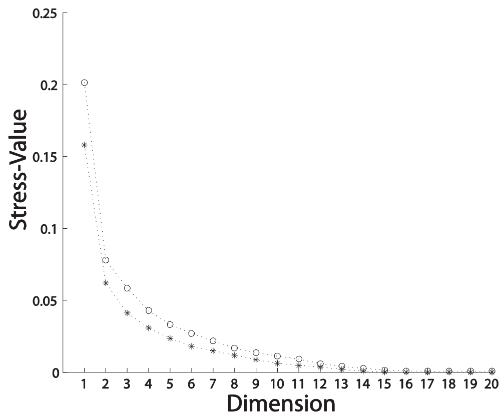

Figure 5 Stress-Values The stress-values for one to twenty dimensions were plotted for the visual modality (stars) and the haptic modality (circles). In both cases the elbow shows that three dimensions were apparent to the participants.

Multidimensional Scaling

We analyzed the similarity ratings performed on the natural sea shells as described previously for the computer generated objects. The similarity ratings were converted to dissimilarities and averaged across participants. The correlations between both modalities were calculated. For the MDS analysis, the stress-values were plotted and the MDS output map was visualized for three dimensions. The goodness-of-fit-criterion between the perceptual spaces of both modalities was also determined.

Results

Two groups of twelve participants rated the similarity between pairs of objects in a visual and haptic condition, respectively. These ratings were averaged across participants and correlated. The correlation is even higher for the natural stimuli compared to the computer generated objects (r=0.968, p=0.00), again showing how similar visual and haptic shape perception was in these experiments.

The stress-values indicate that visually and haptically participants mostly relied on three dimensions (Figure 5). Other dimensions are apparent to the participants as well but play a minor role in judging similarities. We will have a closer look into these details in further analyses. Based on this result we plotted the MDS for three dimensions (Figure 6) and calculated the goodness-of-fit-criterion for the two output maps. In line with the high correlations, the two perceptual spaces were found to be even more similar for the natural objects than for the computer generated objects (goodness-of-fit of only d=0.072).

As can be seen in Figure 6, the perceptual spaces of both visual and haptic exploration not only are highly congruent, but also exhibit a very consistent clustering of the different stimulus groups. Objects 1-4 and 21-24 result in two distinct groups but are direct neighbors in the perceptual spaces although objects 1-4 are gastropods while objects 21-24 are bivalves. The proximity within the perceptual spaces can be explained by the fact that all of these shells are not convoluted while all other shells have a distinct convolution. Objects 5-8 form their own cluster in the perceptual spaces while objects 9-20 form a large group within the visual and the haptic perceptual spaces. The feature most likely to explain this pattern is the form of the aperture. Objects 5-8 have a circular aperture while the aperture of objects 9-20 resembles a groove. Further analysis will compare the shape features to the dimensions of the perceptual spaces in more detail as well as compare the clusters within the perceptual spaces to genetic relations between the sea shells.

Object Feature Validation

MDS provides information about how many dimensions are apparent to participants, but more importantly provides a weighting of these dimensions. Exploring the computer generated shells, participants perceived three dimensions. By correlating the dimensions of the perceptual spaces of the visual and the haptic modality to the dimensions of the physical object space, it will be possible to determine the saliency of the three shape parameters. Cooke (2007) found that shape dominated texture when objects were explored visually while texture dominated shape when objects were explored haptically for objects that varied along the two dimensions shape and texture and concluded that the two modalities complement each other. Further analysis of our data will show if visual and haptic object exploration has a complementary character for our stimulus set as well.

Analyzing the MDS maps of the real shells experiments will also show if visual and haptic object exploration weighted the dimensions equally or not. However, beyond the already highlighted clustering, it will be challenging to correlate the dimensions of the perceptual spaces to clearly defined object features as there is no physical object space with which we can correlate the perceptual spaces. A further, more detailed analysis taking into account also the questionnaires of the participants will show which shape features were salient.

Summary and Outlook

Participants performed similarity ratings on a set of computer generated, shell-shaped objects visually and haptically. In both modalities participants were able to reconstruct the complex structure of the three-dimensional object space although the shape-parameters we altered were very unintuitive. Furthermore the visual and the haptic perceptual spaces were very similar to each other providing evidence that one perceptual space is formed that is accessible to both modalities.

With the set of natural sea shells we were able to extend these findings to natural objects. Again, the results show that humans perceive similarity in the same fashion in both modalities.

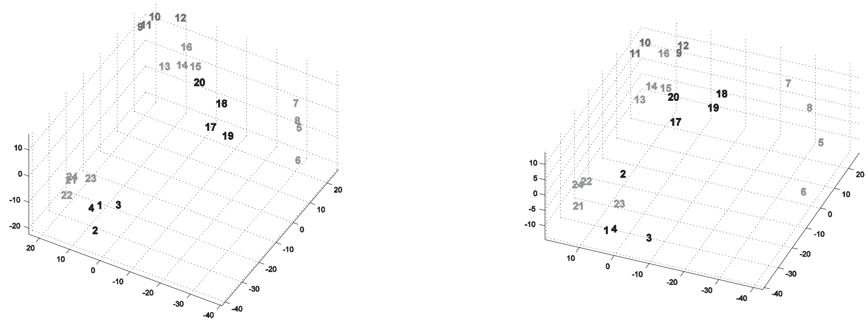

Figure 6 Perceptual Spaces Positions of stimuli in a three-dimensional visual (left) and haptic (right) perceptual space. Objects are numbered according to Figure 4. Shells within one column of Figure 4 are closely related and are marked with the same shade.

The results show highly congruent perceptual spaces in both modalities. Whether it is one underlying space or just congruent, but separate spaces, needs to be determined in future experiments. Participants will learn objects visually and haptically and afterwards recognize them using the same or the other modality. One underlying space should show no effect of modality change while congruent spaces should show an effect. Furthermore, fMRI experiments could show if visual and haptic exploration of these objects activates the same or different brain areas.

Further analysis of the presented results is necessary as well. The perceptual spaces of the natural objects clearly showed that participants did not focus on color in the visual domain and not on material properties in the haptic modalities (also shown by questionnaires). Why did participants clearly focus on shape to judge similarities? One reason might be that color is not a very diagnostic feature for shells in general (e.g. an algae cover could easily change the color and the reflectance of a sea shell). Similarly, relying on fine-grained texture of the object may also be unhelpful because water and sand can smoothen the surface of the sea shells. But both features may become more salient if more objects of only one superfamily are explored. This will be investigated in upcoming studies.

We suggest that humans rely on shape when judging similarities of objects because shape is determined by evolution and by physical parameters. Therefore we are very interested in seeing if cluster analyses of the similarity ratings can predict family resemblance of the objects and is correlated to genetic variation. Upcoming analyses will show if this hypothesis can hold.

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