HAPTIC AND VISUAL DIMENSIONS OF PERCEIVED SOFTNESS

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By

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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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September 2017

Exploring the environment with our senses is a prerequisite to successfully and efficiently interact with it. Our senses provide information about what material objects and surfaces are made of and help us to stay clear of icy patches or using the right grip of force when grasping an oily bottle. Compared to other material properties, the perception of softness has received only limited attention in the haptic and visual perception studies. Moreover, in the haptic domain, softness had been thought of synonymously with compliance. Yet, softness can have many dimensions: the softness of silk and jelly are quite different. Although silk and jelly comply with the force that is applied to them in a similar manner, the perception of softness for these compliant materials are quite different. Using a rating task we investigate here the haptic dimensions of perceived softness and compare it to the haptic dimensions derived from vision only. Results of an exploratory factor analysis suggest that for our set of stimuli, softness has indeed more than one qualitative dimension, i.e. compliance, to it. However, factor loadings were more distinct for the haptic domain. Haptic and visual domains provided rather similar information regarding slipperiness, softness, deformability and roughness. There were, however, differences between the two perceptual domains for granularity, stickiness and hairiness. We discuss these results with respect to the role of haptic and visual information in the perception of softness.

***Keywords**: haptics, vision, softness perception, dimensions of softness, exploratory factor analysis, factor analysis with varimax rotation*

ÖZET

ALGILANAN YUMUŞAKLIĞIN HAPTİK VE GÖRSEL BOYUTLARI

Fatma Seyhun Üstün

Nörobilim Yüksek Lisans Programı, Yüksek Lisans

Tez Danışmanı: Katja Doerschner

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Çevremizle başarılı ve etkin bir biçimde etkileşimde bulunmak için duyularımız ile keşfetmek bir ön koşuldur. Duyularımız objelerin ve yüzeylerin hangi materyalden yapıldığı ile ilgili bilgi sağlayarak bize buzlu bir yoldan uzak durmamız, yağlı bir şişeyi tutarken doğru kavrama gücünü kullanmamız gibi durumlarda yardımcı olur. Diğer materyal özellikleri ile karşılaştırıldığında, yumuşaklık algısına haptik ve görsel algı çalışmalarında daha az odaklanılmıştır. Ek olarak, haptik alanda, yumuşaklık uyumluluk ile eş anlamlı olarak kullanılmıştır. Bununla birlikte, yumuşaklığın birçok boyutu olması mümkündür: ipeğin ve jelibonun yumuşaklıkları oldukça farklıdır. Her ne kadar hem ipek hem de jelibon kendilerine uygulanan güce benzer biçimde uyumluluk gösterse de, bu uyumlu materyallerin yumuşaklık algısı oldukça farklıdır. Bir derecelendirme görevi kullanarak bu çalışmada algılanan yumuşaklığın haptik boyutları araştırılmış ve bu boyutlar yalnızca görsel bilgiden çıkarılan haptik boyutlarla karşılaştırılmıştır. Keşifsel faktör analizinin sonuçları, bizim uyaran grubumuz için, yumuşaklığın gerçekten de tek bir nitel boyuttan, uyumluluktan, başka boyutları da olduğunu ortaya koymuştur. Bununla birlikte, faktör yüklemeleri haptik alan için daha belirgin olmuştur. Kayganlık, yumuşaklık, biçim değiştirilebilirlik ve pürüzlülük için haptik ve görsel alanlar benzer bilgiler sağlamıştır. Öte yandan, taneciklilik, yapışkanlık ve tüylülük söz konusu olduğunda iki alan arasında sağlanan bilgi açısından bir fark gözlenmiştir. Makalede bu sonuçlar, yumuşaklık algısında haptik ve görsel bilginin rolleriyle ilişkili olarak değerlendirilmektedir.

Anahtar sözcükler: *haptik, görsel, yumuşaklık algısı, yumuşaklık boyutları, keşifsel faktör analizi, varimaks döndürmeli faktör analizi*

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

"Intellectual growth should commence at birth and cease only at death."

Albert Einstein

Exploring the environment with our senses is a prerequisite to successfully and efficiently interact with it. By touching or looking humans can distinguish, in a split second, between different materials such as soft rabbit fur and rough wooden bark, or smooth silk and stretchy latex. We engage in many behaviors of touch or vision when we interact with the materials around us. When for instance stroking a pet bunny, squeezing a sponge when washing the dishes, feeling the silk garment we intend to buy, wiggling the jelly pudding when we eat, looking at our fuzzy carpet, choosing the most comfortable sofa when we visit a friend, determining the best area of grass by looking to have a picnic etc. As a result of these interactions with the environment, we quickly decide about the material's properties such as its glossiness, slipperiness etc.

In the most general terms, object perception has gathered attention in the literature investigating size and shape perception. Regarding material perception, color has been a focus in the studies and it was studied visually. A lot of progress has been made in the visual perception literature on the perception of materials. However, haptic perception of material qualities still largely remains unstudied.

In haptic literature, Yoshida's multidimensional studies and subsequent early studies by other scientists (Lyne et al., 1984; Hollins, Faldowski, Rao, & Young, 1993), revealed the dimensions of touch perception as heaviness/coldness, wet/smoothness and hardness (Yoshida & Yoshida, 1968). In a review, from eighteen studies of touch perception, Okamoto et al. summarized five main dimensions of touch as macro and micro roughness, warmness, hardness and friction (moistness and slipperiness). Haptic studies that focused on material perception majorly investigated roughness and hardness of materials, out of these five categories and softness remained to be a subject of less focus and few studies investigated softness perception. In these smaller number of studies, softness was considered to be an equivalent of compliance. In other words, softness is defined in relation with the compliance (Drewing, Ramisch, & Bayer, 2009) and elasticity (W.M. Bergmann Tiest & Kappers, 2009) of a material, and arises from contact with the surface of a deformable object (Klatzky, Roberta L.; Pawluk, Dianne; Peer, 2013). Compliance is defined as a property that depends on the force applied to the object and its consequential deformation (Cellini, Kaim, & Drewing, 2013). Thus compliance could potentially provide rich information for recognizing materials (Wouter M. Bergmann Tiest & Kappers, 2006). Consequently, for instance, playdough, aluminum foil and sponge are considered soft because they comply with the force that is applied to them. It is not surprising therefore that, the haptic studies focusing on softness mostly manipulated the compliance of a stimulus. However, a soft rabbit fur feels quite different than soft jellybean or soft silk. Although these all are compliant materials, the perception of softness varies among them. Therefore, it can be argued that there might be other dimensions to softness other than only compliance. The difference of softness between the compliant materials may be due to other dimensions that softness possesses. It is not known yet what these dimensions are, however; it is a possibility that other material properties such as hairiness, density, elasticity, size, weight, plasticity or slipperiness may play a role. The present study is primarily focused on mapping the dimensionality of perceived softness. It primarily aims to investigate the haptic perception of softness, and to explore the haptic information derived from vision, in addition.

Why Study Vision?

Although softness is a concept that might be considered to be perceived more by touch, we visually detect softness of materials around us every day; curtains moving in the wind, a flip of hair, the fuzzy look of wool, the comfortable look of a chair, fluffy looking pillows etc. Touching a material provides haptic information obviously; however seeing a material also provides haptic information as can be seen in the examples given above. In the present paper, the former is referred to as “direct information” and the latter is referred to as “indirect information”; meaning that the haptic information that arises from touch behavior is direct and haptic information that arises from visual behavior is inferred or derived. Our study aims to investigate the information that is provided by haptics or vision for influencing the softness perception. The direct information that is gathered by touch evidently plays a role in softness perception; but what about the indirect haptic information that vision provides? What kind of haptic information we obtain via visual behavior? How do we detect the elasticity or roughness or hairiness of a soft object by looking? Is the information derived from vision similar to what is obtained via haptics? Does vision in any manner add new information to our haptic perception? It is our aim to investigate these questions by exploring the contributions of these two types of information to the dimensionality of perceived softness.

Along with the direct haptic information, indirect sensory visual input might provide information that allows us to infer softness of a material. A study on compliance by Drewing et al. (2009) showed that vision alone was sufficient for participants to discriminate between the softness of the stimuli. More specifically, in this study, watching another person’s finger movements who is interacting haptically with an object provided information regarding the deformation of the surface.

Cue-conflict works of Srinivasan (1999), Cellini et al. (2013) and Drewing et al. (2009) tried to assess the amount of information that the vision and/or haptics provide to the haptic perception. Although the exact amount of contribution of visual and haptic information to the haptic perception is a subject of controversy due to opposing results, it is commonly accepted that the resulting haptic perception is an equation of both visual and haptic input and an intermodal integration takes place between vision and haptic modalities in the perception of softness.

It can be said that softness perception is a very complex process that is performed by vision and/or haptic domain and the interaction between the two modalities affects the resulting perception greatly. Therefore, studying the contribution of vision into haptic perception is inevitable. Taking these points into account; our primary interest is to study whether the softness dimensionality is different for vision and haptic domains. In order to observe the effect of haptically provided information and visually provided information, and not the effect of their interactions, we conducted two different experiments with conditions haptic-only and vision-only to see the information haptics provides alone and the information vision provides alone. Our two main aims can be stated as i) to explore the haptic dimensions of softness and ii) to investigate the information that is derived from vision only.

Chapter 2

Methods

Experiment I

In order to investigate the haptic information that is derived from haptic exploration only we conducted Experiment I, in which the participants merely touched at the material without seeing it.

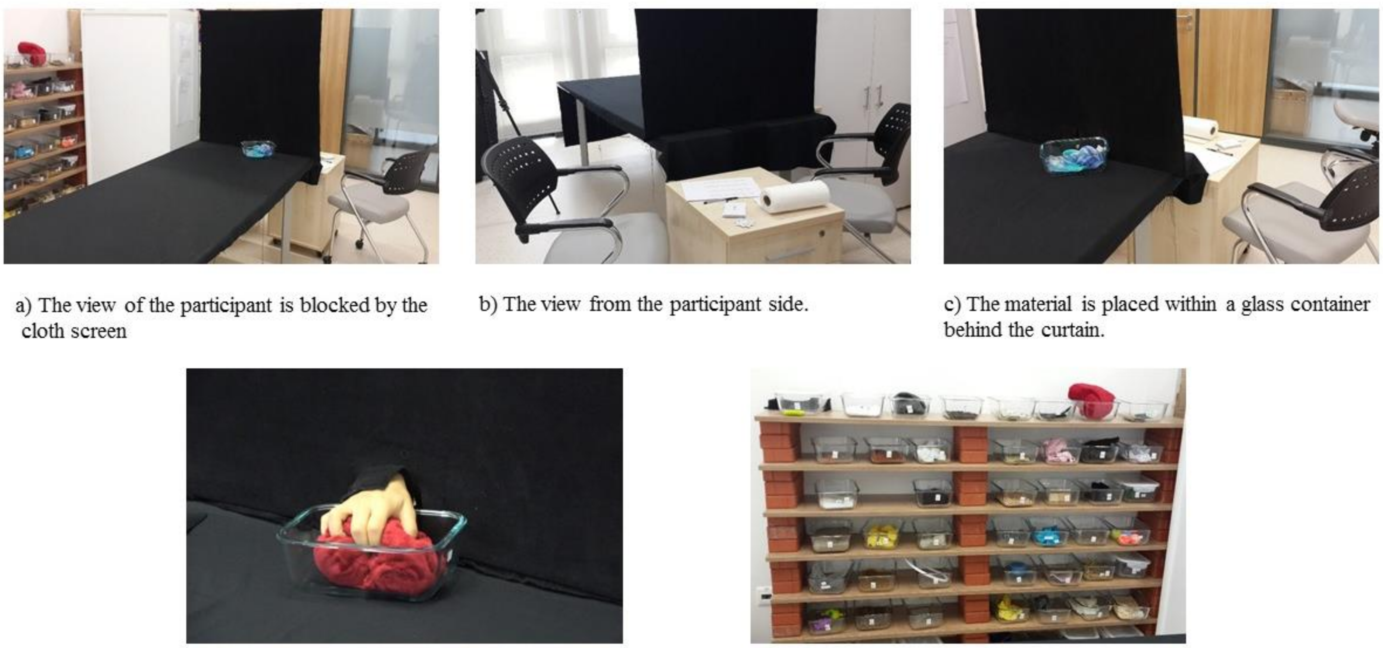
Participants

There were 34 participants initially in the experiment I, however 2 of the participants' data were eliminated due to internal inconsistency because Cronbach's alpha values were not significant for these participants. The resulting data set was composed of 32 participants (15 female and 17 male). The age ranged between 19 – 29, average age was 23.71 years. None of the participants had touch related disabilities.

All participants were given a written form describing the aim of the study. Each participant had signed a consent form and was informed their participation was voluntary and they were able to stop the experiment at any given point in case they feel disturbed for any reason. The participants were told they would receive 30 TL once the experiment was finished and they were paid after the experiment had finished. Each participant completed the experiment as one experiment lasting approximately ninety minutes.

Experimental Setup

The experiment was conducted in a room where the temperature was adjusted to 23C degrees and illumination in the room was also controlled by having the lights on and curtains down at all times. The task was explained verbally by the experimenter in standardized sentences before the initiation of the trial (please see Appendices A and B for the standardized instruction in English and Turkish, respectively). Participants were asked to wear ear and nose plugs in order to eliminate any auditory or olfactory information that might occur during the discovery of the item. Participants only touched the material behind a cloth screen. The physical experimental setup can be seen in Figure 1.



a) The view of the participant is blocked by the cloth screen

b) The view from the participant side.

c) The material is placed within a glass container behind the curtain.

d) The participant inserted the hand to touch the material.

e) 50 items are presented one by one.

Figure 1. Experimental Setup. The only difference between experiment I and II is that the cloth screen seen in d) is removed in experiment II and the table was put against a wall, participants merely observed the material instead of touching it.

Stimuli

Material Selection Rationale

In the haptic literature, most studies are comprised of artificially produced stimuli, which were not as rich as the materials we often interact with in daily life, such as raised dots (Gescheider, Bolanowski, Greenfield, & Brunette, 2005), aluminum plates with grooves (Lederman & Taylor, 1972), textures (Ballesteros, Reales, De Leon, & Garcia, 2005; M Hollins, Faldowski, Rao, & Young, 1993; Okamoto et al., 2012; Picard, Dacremont, Valentin, & Giboreau, 2003; Yoshioka, Bensmaia, Craig, & Hsiao, 2007) and devices applying different amounts of friction onto the finger (Chubb, Colgate, & Peshkin, 2010) or devices that produce constant force to skin (Guest, Dessirier, et al., 2011) . Stimuli used by other studies such as various paper stimuli (Summers, Irwin, & Brady, 2008), car seats (Picard et al., 2003) and fabrics (Soufflet, Calonnier, & Dacremont, 2004) may be considered more analogous with the materials we experience in daily life. A wider range of stimuli were selected in few studies involving wax paper, cardboard, plastic, nylon, velvet etc. (M Hollins et al., 1993); and foam, carpet, cotton, leather, steel wire, plexiglass, tile etc. (Wouter M. Bergmann Tiest & Kappers, 2006). Fluids were selected as stimuli only in few studies (Guest, Mehrabyan, et al., 2012; Guest, Ma, et al., 2012). In the present study, a wide array of materials is produced by combining the various material types used in the literature (Summers, Irwin, & Brady, 2008; Picard et.al., 2003; Soufflet, Calonnier, & Dacremont, 2004; Hollins et al., 1993; Bergmann Tiest & Kappers, 2006) including solid materials as well as materials with fluidity (Guest, Mehrabyan, et al., 2012) in order to be able to collect data regarding various material properties that may possibly contribute to the dimensions of perceived softness. The materials are selected with correspondence to our aims of i) exploring haptic dimensionality of softness and ii) determining the role of haptic information that is derived from only visual input on this perception.

Materials

We had 5 categories of items: elastic materials, textiles, deformable materials, granulate materials and non-soft materials; 10 items per category, i.e. 50 items in total. Each item was chosen to be diverse and unique in terms of haptic information, in compliance with the abovementioned rationale. Please see Table 1 for a complete list of materials and their respective features which are used as a rationale for the selection of the items and please see Figure 2 for the visual representation of the items used, depicted separately for each respective category (please see Appendix C for complete list of materials shown in a larger scale).

Table 1. Complete list of materials according to five different haptic categories along with the distinctive features

Item Category	Materials	Feature
Elastic	bandage, bouncy balls, juicy toy, lady's stocking, latex, plush pillow, rubber bands, silicone, sponge, white rubber	Elasticity
Textile	cotton, fur, leather, linen, mat, microfiber, polar, silk, velvet, wet cloth	Hairiness, Slipperiness, Thickness
Deformable	aluminum foil, clay, hair gel, hand cream, paper, peeling cream, playdough, shaving cream, slime, wires	Wetness, Density, Plasticity
Granulate	blackpepper, chickpeas, flour, foam, pinecone, poppyseeds, red pepper, sand, sawdust, sugar	Size, Weight, Hardness
Non-soft	brick, cardboard pieces, chalk, glass, hard plastic, metal nuts, sandpaper, stone, straw, wood	Non-plasticity, Non- Elasticity

Figure 2. Fifty items visually represented in the respective categories; a) textile materials, b) granulate materials, c) deformable materials, d) elastic materials e) non-soft materials

Adjective List Selection Rationale

Haptic Lexicon

Unlike modalities such as audition and vision, touch is a modality that is frequently found more difficult to be put into words in daily life other than very basic definitions such as hot/cold or hard/soft; also the nuances are many in the touch perception and most languages lack the exact words to describe the feeling. Likewise, the interpretation of the results by people with different mother tongues would be expected to be complicated due to the differing capacities of languages in describing haptic phenomenon. Not surprisingly, when investigating the expression of touch;

the nature of the richness and differences in languages has become a hindrance for standardizing the manner participants articulate their perception of touch. Therefore, studies of touch needed a lexicon in order to gather a relatively standardized information regarding the perceptual experience. Although a list of the actions applicable to tactile and haptic exploration existed (Lederman & Klatzky, 1987, 1990); these procedures lacked the use of a lexicon and included non-verbal tasks such as usage of numerical rating scales (Baumgartner et al., 2013), or finding a target contour merely by touch (Chubb et al., 2010), or usage of two-alternative forced choice for detecting target material (Ho & Jones, 2006; Mark Hollins & Risner, 2000). The verbalization of touch experience is not included in the majority of the studies. It is considered that there are two tactile layers (Okamoto, 2012): psychophysical i.e. physical properties such as roughness or elasticity, and affective i.e. perceptual properties such as richness and kindness. Non-verbal measures might be successful in assessing the physical properties to an extent, however; affective aspects of touch perception certainly require the use of language. In an attempt to create such a lexicon in English Guest et.al (2011) reviewed the touch literature and created a 262 adjective list and had English-speaking people rate how much a given adjective is related to touch. Then, the list was reduced to 168 adjectives. Other studies adapted this study to different languages (e.g. see the study in German by Drewing, Weyel; Celebi, Kaya in Giessen University, not published). In compliance with this method we adapted this methodology to the Turkish language.

While physical properties are widely studied in the previous work, emotional attributes of touch perception remained to be an open question. Although some studies included pleasantness or comfort as an attribute, the details remain unclear (Guest et.al 2011). In our study, 31 adjectives that are related to both physical and affective properties of materials were used, aiming to shed light upon the affective material perception as well as the previously searched physical properties.

Adjective list adaptation

With regard to the necessity of use of a haptic lexicon stated above, we adapted the adjective list in English from Guest et.al. (2011) to Turkish. First, we gave the list consisting of 262 touch-related adjectives to 7 English-speaking people in Giessen University and have them select the adjectives if they thought the adjective is sensual. The resulting English list was narrowed down to adjectives pertaining to the focus of the study, i.e. softness. Afterwards, we grouped the similar adjectives in English and eliminated either of the adjectives that are too similar for the purpose of making the list effective. Studying on this list, we selected adjectives that we think mostly apply to the materials in our study and we eliminated the adjectives that has no relation to our materials (such as watery) or to our aim of assessing softness perception (for instance, adjectives that are related to shape perception). Following this, the translation of the scale from English to Turkish is performed by 3 multilingual people and the translated list was evaluated by 3 people who speak both English and Turkish to ensure the correspondence between the translation and the original list. After the translation we grouped Turkish adjectives that are similar in the meaning again and we eliminated similar adjectives; in cases that some of the translated versions of different English adjectives were expressed in very similar words in Turkish. Emotional adjectives were sacrificable (such as calming) since our study focuses on the physical properties of the materials rather than the sensual perceptions; however, we included a few words that were considered to be more related to sense of comfort in a physical manner (such as fluffy or airy). For instance, we used sticky instead of viscous, because it correlates with viscosity and the word-by-word translation of the adjective "viscous" is not used in Turkish. We included both adjectives flexible and inflexible in order to make sure that the participants are paying attention to the task; in cases which these two adjectives were scored too similarly by the same participant for the same material; that would suggest the data of this particular participant would be inconsistent, probably due to lack of attention. Such data are eliminated in the analysis process.

The aspect of this study which is distinctive in comparison to previous studies is that we aim to investigate the haptic perception of softness dimensions and compare the information that is extracted from haptic exploration versus visual exploration. Therefore, the most important aspect of the adjective selection was to include adjectives that are related to the two modalities in a manner that some of the adjectives require direct haptic information and inferred visual information regarding the judgment of haptic properties of the material, while some require direct visual information and inferred haptic information. Adjectives such as glossy, rough or granular were specifically included because these are material properties which provide tactile information from visual experience. It was our goal to see how the ratings of these adjectives are affected in touch-only and vision-only conditions.

As stated in the introduction; some haptic information comes from haptic behavior, some haptic information comes from visual behavior; we refer to the former as direct and the latter as indirect. The adjectives in the list are selected to reflect this distinction; some required direct haptic information whereas some adjectives required a derivation of haptic information from the visual behavior; i.e. participants had to rate an adjective that requires haptic information based on their visual experience by deriving the haptic information from visual information. Our experimental design is aimed to observe how much of the haptic dimensions of softness are extracted from only haptic input or only visual input.

Adjective List

As described above, a list of adjectives consisting of 31 Turkish adjectives in total was used in the experiment; please see Table 2 for a full list of adjectives selected along with their Turkish translations. In the table, the direct or indirect (inferred) information the respective adjective requires may be observed.

Table 2. List of 31 adjectives and the respective transference features between vision and touch.

Adjective in English	Turkish Translation	Direct or Indirect information the adjective requires
fluffy	kabarık	Direct both for haptic and visual
scabby	kabuklu	Direct both for haptic and visual
sandy	kum gibi	Direct both for haptic and visual
woody	odunsu	Direct both for haptic and visual
scaly	pul	Direct both for haptic and visual
roughened	pürüzlü	Direct both for haptic and visual
granular	tanecikli	Direct both for haptic and visual
powdery	toz gibi	Direct both for haptic and visual
hairy	tüylü	Direct both for haptic and visual
malleable	biçimlenebilir	Direct for haptic, Inferred for visual
textured	dokulu	Direct for haptic, Inferred for visual
elastic	esnek	Direct for haptic, Inferred for visual
inflexible	esnemez	Direct for haptic, Inferred for visual
meaty	et gibi	Direct for haptic, Inferred for visual
compliant	güç uygulanabilir	Direct for haptic, Inferred for visual
doughy	hamursu	Direct for haptic, Inferred for visual
delicate	hassas	Direct for haptic, Inferred for visual
silky	ipeksi	Direct for haptic, Inferred for visual
gelatinous	jölemsi	Direct for haptic, Inferred for visual
velvety	kadifemsi	Direct for haptic, Inferred for visual
slippery	kaygan	Direct for haptic, Inferred for visual
moisturous	nemli	Direct for haptic, Inferred for visual
hard	sert	Direct for haptic, Inferred for visual
slimy	sümüksü	Direct for haptic, Inferred for visual
spongy	süngerimsi	Direct for haptic, Inferred for visual
airy	tiril	Direct for haptic, Inferred for visual
gooey	vıcık	Direct for haptic, Inferred for visual
sticky	yapışkan	Direct for haptic, Inferred for visual
Soft	yumuşak	Direct for haptic, Inferred for visual
Leathery	derimsi	Direct for haptic, Inferred for visual
Glossy	parlak	Inferred for haptic, Direct for visual

Procedure

Semantic Differential Method

In the present study, the Semantic Differential Method (SDM) is used to map the dimensionality of the haptic perception. It was first used by (Yoshida & YOSHIDA, 1968) and this method is characterized with the usage of a lexicon. The participant rates the presented material on a given adjective depending on his/her opinion regarding how much the adjective corresponds to the material. The scale generally consists of 5 or 7 points. The lowest number indicates that the given adjective does not apply to the material at all and the highest number indicates that the given adjective applies to the material completely. This method is used in several studies (Evans & Wilkins, 2000; Shao, Chen, Barnes, & Henson, 2010; Yoshida & YOSHIDA, 1968; Chen, X., Shao, F., Barnes, C., Childs, T., & Henson, 2009; OSGOOD, 2009). The advantage of this method is that each factor is explained by a number of factors or factor combinations; therefore no additional experiments are required as in other methods to map fundamental tactile factors in the experiment. However, an important point here is to select the adjectives in a manner to cover all possible dimensions. Hence, we opted for adjectives which relate to many perceptual dimensions stated in the literature. Originally Osgood et.al (2009), used bipolar scales, for instance one end of the scale was “good” and the other end was “bad”; and these adjective pairs were used to provide information about the connotation of the words. In our study however; we adopted this technique to a unipolar scale, each rating corresponded to only one adjective and we aimed to know how relevant they are to the material being explored.

Active Touch as a Procedure for Haptic Exploration

The procedure of interacting with the material is a significant aspect in the haptic studies. Tactile perception is defined as the passive perception of material properties where the finger or hand is immobile and stimulated by a moving external stimulus (Ballesteros & & Heller, 2008). Passive touch was often used in the previous studies where participants were told to keep their finger static and the material beneath was moved (Hollins, Bensmaïa, Karlof, & Young, 2000) or participants merely touched the given material with one stroke of a finger and without further movement of hand or finger to perform a richer movement such as sliding (Jones & Berris, 2003). Passive touch studies unveiled significant information about the perception of particular stimuli including raised dots, raised line pictures; i.e. stimuli that elicit a friction perception. However, haptics is a broader concept with a meaning of "related to touch" and haptic sensation of touch results from active and exploratory hand and finger movements (Ernst, Banks, & Bülthoff, 2000). In other words, it is possible to think haptics as the sense occurring in active touch. Rather than the passive touch, haptic modality plays an important role for humans to perceive material properties of three dimensional objects and to engage in an interaction with them (Gentaz, 2009). Active touch is the case where participants are enabled to freely explore the given material. Research suggest that there is a difference between active and passive exploration in terms of the information they provide (Bicchi et al., 2005). Active touch provides richer information for perceiving the material properties and is a procedure that is close to how we interact with materials in real life. An educated guess may be made that active touch would be expected to result in more information of material properties than the passive touch allows. Indeed, it is supported by evidence that passive touch and active touch provide different information (Mark Hollins & Risner, 2000; Srinivasan & LaMotte, 1995). It can be argued that studies conducted with mere passive touch procedures might miss some significant aspects of haptic material perception which are different than friction, for as much as the tactile sense is not a passive experience and the sensations are actively selected according to the goals of exploration (Gibson & J., 1962). Therefore it can be said that the methodology in touch studies plays a significant role since the data obtained in a particular manner may either reflect or overlook some aspects of material perception. Consequently, a free exploration of active touch is preferred in the touch experiment of the present study for the purposes of gathering information of touch perception as close as to what is experienced in daily life. In the present behavioral procedure, participants explored the materials freely with using only the right hand: they squeezed, caressed, broke, and pinched etc. the materials. These free explorations were video-recorded for another study that focuses on the free exploration procedures in active touch (Lubna, Knut Drewing, University of Giessen, 2017).

It is suggested that the planning of hand movements is modified based on the visual perception of the materials (Buckingham, Cant, & Goodale, 2009) and simultaneous visual and haptic information alters the haptic perception in favor of visual dominance (Rock, I., & Victor, J. (1964) and in cases where vision is not dominant at least a compromise between the senses occurs (Heller, 1992). Therefore, we conducted haptic-only and vision-only behavioral experiments separately in order to eliminate the possible effect of one modality over the other when the haptic perception is being shaped.

Experimental Procedure

A 2-point touch discrimination test was used prior to the experiment to ensure that the touch perception of the participant is among normal range. A plastic measurement tool was used to apply 2 points with varying intervals to the index finger of the participant when s/he is not looking at the tool and their hand. The application of different intervals was random. They were asked to tell how many points they felt touching. If they replied correctly the number of points applied to them with the minimal interval 3 times, they were considered to have intact touch perception.

Items were stored in glass containers separately and one item in a glass container was located behind a screen by the experimenter at a time. The participant was not able to see the present item or any of the remaining items; their vision was completely blocked by a clothed screen. The participant put their right hand in through an insert located in the center bottom of the screen and touched the given item as long as and in any manner they would prefer. Their behavioral hand movements were not instructed, the experimenter stated clearly that the participant was free to discover the given item in any manner they would favor. While touching the item, the participant was asked to score a list of adjectives from 1 to 7, one adjective at a time. This Semantic Differential Scale was designed to assess how much a given adjective was applicable/ suitable to the item that was being discovered. Adjectives were presented visually on mini cards, in order to eliminate the experimenter's effect in relation to the adjectives as much as possible. A mini card with an adjective written in the center was shown to the participant, the participant responded by saying a number between 1-7; 1 indicating that the adjective is not relatable at all to the item and 7 indicating that the adjective is very much relatable to the item. The experimenter wrote down the score, showed another card, received the response, noted the respective response until the full list is shown and scored. Each adjective was shown only once per item, the order of adjectives being shown was randomized for each material. The participant had 3 seconds to respond to an adjective for time-management purposes, in cases it took more than 3 seconds for the response an auditory feedback (a simple beep sound) was provided to the participant for them to respond and move to the next adjective.

Once the complete list of adjectives was scored for one item, the item was removed and the next item in a glass container was presented. The participant's hand movements were recorded in a video camera anonymously for each item. These videos are used in a separate study to understand touch behavior in detail (please see Drewing et.al. 2016). The video recordings were recorded by a Sony camera with a frame of 50p, file format was XAVC SHD and the resolution was HDMI 1080p. In cases needed, the participant was provided with paper towels and wet towels after the discovery of specific items such as hair gel or shaving cream. It was ensured that the participants' hand is clean and dry before the discovery of each item.

Data Analysis

First a consistency analysis was conducted on the dataset of the respective experiment in order to determine to what extent the participants' responses were consistent. Thus, pair-wise correlations of any two participants' scores across all adjectives and materials were calculated. In addition, to determine the consistency of all participants for a specific adjective, Cronbach's alpha between participants was calculated for each adjective separately. After the data was determined to be sufficiently consistent for further analysis, we conducted Factor Analysis for each adjective in order to see how much of the variance in the data was explained by a factor or several factors. Thus, responses of all participants for one adjective and material was averaged. This resulted in, for instance, one averaged score for adjective 'compliant' as a response to material 'stone'. After obtaining averaged scores for each adjective-material combination, we performed a covariance based factor analysis with varimax rotation as a principle component analysis, which is an exploratory factor analysis procedure. We used Keyser-Meyer-Olkin (KMO) and Barlett's test of sphericity as criteria to determine whether the correlations in the data were statistically meaningful and it was plausible to conduct Factor Analysis. KMO measures the sampling adequacy for each variable and is a measure of proportion of variance among variables. When this proportion is low, it means the data is suited for Factor Analysis. Barlett's test of sphericity shows how much the data is valid and suitable to the problem being addressed in the study. Upon obtaining significant results in KMO and Barlett's test, we conducted a covariance-based factor analysis with varimax rotation in order to determine the factors which may explain the variance in the data significantly.

Results

The consistency analysis revealed a good consistency of adjectives among the ratings of the participants, thus, it can be said that a variance observed in the data shall be due to a true factor rather than to a random effect of inconsistent scoring distributions. In order to assess internal consistency we performed Cronbach's alpha analysis and results revealed good consistency with Cronbach's alpha values above .9.

The initial Cronbach's alpha values obtained were very high for each adjective. However, the consistency analyses revealed that the data of two participants were inconsistent compared with the distribution of the rest of the participants for each and every adjective, i.e. corrected item total correlation values of these two participants were below 0.4 and the data deviated extremely from the correlation values of the other participants (corrected item total correlation values signify the correlation of one participant with all the other participants combined.). Therefore, these two participants were excluded from the analysis in order to work with an internally consistent dataset. Upon exclusion, the Cronbach's alpha for each adjective is re-calculated and the results, again, revealed high Cronbach's alpha values for each adjective. As it can be seen in Table 3, Cronbach's alpha values for each adjective in touch experiment suggest excellent consistency and the range of Cronbach's alpha varied among .958 and . 986. Also, correlation analysis between adjectives has been performed; inter-item correlations suggested good consistency, the range was between .579 to .953, 19 of 31 adjective correlations had values greater than .7.

Table 3. Cronbach's alpha values for each adjective in the touch experiment

Adjective	Cronbach's Alpha	Adjective	Cronbach's Alpha
malleable	0,973	moisturous	0,979
leathery	0,981	woody	0,977
textured	0,964	glossy	0,958
elastic	0,978	scaly	0,97
inflexible	0,964	roughened	0,974
meaty	0,975	hard	0,977
compliant	0,984	slimy	0,973
doughy	0,977	spongy	0,982
delicate	0,976	granular	0,972
silky	0,974	airy	0,944
gelatinous	0,984	powdery	0,986
fluffy	0,985	hairy	0,978
scabby	0,957	gooey	0,983
velvety	0,975	sticky	0,966
slippery	0,966	soft	0,986
sandy	0,972		

Since the correlations of items were high, an Exploratory Factor Analysis shall reveal an underlying latent variable that explains these correlations. The KMO score for this experiment was .697 and Barlett's test of sphericity was significant ($\chi 2$ (465) = 2321.192 , $p<0.001$); suggesting that the overall significance of all correlation within the matrix were meaningful and it was plausible to conduct Factor Analysis on the data.

Kaiser-criterion was used in extraction of the factors. Factor Analysis revealed six factors in the touch data, explaining the 86.456 % of the variance in total, please see Fig.3 for the scree plot of adjectives.

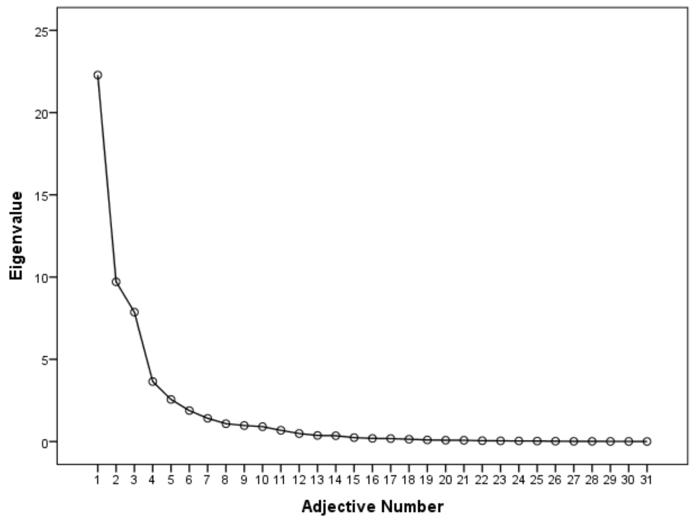


Figure 3. Scree plot of Factor Analysis for 31 adjectives in experiment I

In order to obtain a criterion value to determine factor loadings; communalities of adjectives is used. Square root of 30% of the mean variance of the communalities is obtained as a criterion score; please see Table 4 for the criterion value. Each adjective above this cut-off value is highlighted with light grey in the Table 5. The adjectives that are highlighted with dark grey if the loadings is maximal across factors.

Table 4. Criterion value as square root of 30% of mean variance per adjective

Communalities	
malleable	1,523
leathery	,517
textured	1,210
elastic	2,743
inflexible	2,680
meaty	,532
compliant	1,088
doughy	2,179
delicate	1,166
silky	,971
gelatinous	2,028
fluffy	1,326
scabby	,702
velvety	1,769
slippery	1,346
sandy	2,786
moisturous	1,553
woody	1,190
glossy	1,305
scaly	1,491
roughened	2,282
hard	3,481
slimy	1,596
spongy	1,770
granular	3,646
airy	,677
powdery	2,745
hairy	1,550
gooey	2,336
sticky	1,922
soft	3,354
Mean	1,789125
30% of Mean	0,536738
Sqrt of 30% of Mean	0,732624

Table 5 shows the factor loadings in the touch experiment. Two criteria are used in order to determine the adjectives in each factor loading: a) the adjective must have a value greater than 30% of mean variance per adjective and b) the adjective loads highest on a specific factor compared to its loadings on the other factors.

Table 5. Factor loadings for experiment I

	Experiment I					
	Factor Loadings I-VI a,b					
	I	II	III	IV	V	VI
	Deformability	Fluidity	Hairiness	Granularity	Roughness	Density
inflexible	-1,41	-0,3	-0,256	0,255	-0,127	-0,465
elastic	1,388	0,217	0,056	-0,411	0,008	0,615
compliant	0,843	-0,009	-0,205	-0,37	-0,137	0,114
delicate	0,862	0,159	0,235	-0,143	-0,178	-0,162
soft	1,461	0,735	0,685	-0,224	-0,026	0,047
hard	-1,468	-0,611	-0,809	-0,015	-0,116	-0,175
spongy	0,903	-0,077	0,245	-0,204	0,645	0,015
malleable	0,834	0,373	-0,007	-0,104	-0,085	0,448
woody	-0,686	-0,197	-0,384	-0,015	0,334	-0,112
fluffy	0,671	0,099	0,192	-0,076	0,504	-0,07
moisturous	0,129	1,195	-0,052	-0,03	-0,222	0,05
gooey	0,264	1,453	-0,025	-0,026	-0,211	0,227
sticky	0,113	1,303	-0,064	0,001	-0,201	0,094
slimy	0,261	1,181	-0,123	-0,12	-0,193	0,13
gelatinous	0,454	1,246	-0,165	-0,162	-0,252	0,162
velvety	0,226	-0,161	1,171	-0,131	0,345	0,048
silky	0,278	-0,049	0,828	-0,107	-0,137	-0,141
hairy	0,103	-0,093	1,045	-0,134	0,389	0,04
airy	0,062	-0,054	0,559	0,197	-0,091	0,002
leathery	0,21	-0,039	0,37	-0,193	-0,014	0,327
sandy	-0,321	-0,05	-0,034	1,565	0,085	-0,057
powdery	-0,291	0,001	0,173	1,544	0,081	0,125
granular	-0,238	-0,345	-0,475	1,608	0,3	-0,613
scaly	-0,347	-0,078	-0,109	0,82	0,515	0,053
textured	0,016	-0,333	0,343	0,005	0,861	-0,169
roughened	-0,157	-0,563	-0,09	0,475	1,091	-0,471
slippery	0,021	0,621	0,169	-0,269	-0,814	-0,309
glossy	-0,049	0,171	-0,092	-0,304	-0,747	-0,383

scabby	-0,367	-0,134	-0,327	0,201	0,381	-0,112
meaty	0,191	0,266	-0,037	-0,046	0,026	0,535
doughy	0,615	0,857	-0,036	-0,001	-0,081	0,876

Extraction Method: Principal Component Analysis.

a. Light gray if the loading is > 30% of the mean variance per adjective
b. Dark gray if the loading is > 30% of the mean variance per adjective *and* the loading is maximal among factors

Here, the first rotated factor explains 24.5% of variance in data. The adjectives, “elastic”, “compliant”, “delicate”, “soft”, “spongy”, “malleable” (positive loadings) and “inflexible”, “hard” (negative loadings) load in this factor. Taken together, the elasticity (elastic, compliant, delicate, and inflexible, hard in reverse meaning) and density (spongy, malleable) of the material might explain this factor loading. Along with elasticity and density, for negative loadings non-deformability seem to contribute to the loadings of the adjectives inflexible, hard and woody. Overall, this factor may be defined by *deformability*.

The second factor explains 20.36 % of variance. Adjectives “moisturous”, “gooey”, “sticky”, “slimy” and “gelatinous” load high on this factor. Slipperiness, wetness and density features of materials seem to play a combined role in the loading of this factor. Therefore, this factor may be labeled with *fluidity*.

The third factor explains 10.31 % of variance. Adjectives “velvety”, “silky” and “hairy” load on this factor. Taken together, *hairiness* seems to be effective in the loading of this factor.

The fourth factor explains 16.56 % of variance. “Sandy”, “powdery”, “granular” load very highly on this factor, along with a relatively lower loading of adjective “scaly”. We think the material features which explain this factor loading are the ones related with features of a combination of size and weight, i.e. a combination of small size and plural particles: thus, this factor is labeled as *granularity*.

The fifth factor explains 9.15 % of variance. “Roughened”, “textured” load high on this factor along with “slippery” and “glossy” (negative loadings). Overall *roughness* material property seems to define this factor. “Glossy” is an important adjective because the judgment it requires is transferred from touch perception. The fact that it is loaded along with other adjectives related to slipperiness holds significance; both slipperiness and glossy have negative loadings.

The sixth factor explains 5.54% of variance. Only the adjective “doughy” loaded on this factor. However, “meaty” also seem to take its highest loading in this factor than it took in other factors, although not significant. Considering doughy and meaty together, the material properties of *density* seem to play a role together in this factor loading.

Discussion

For haptic judgments, we can see there are 6 factor loadings. Factors deformability and fluidity have high factor loadings; meaning that these are two material properties that are mostly judged by touch in comparison to other factor loadings with low values, such as density. In relation to softness perception, it can be said that deformability, fluidity, hairiness, granularity, roughness and density properties of the materials play an important role when we perceive the material, and its softness, haptically.

Adjectives woody, fluffy, airy, leathery, scabby and meaty did not load in any factor. It might be said that these adjectives were not suitable for haptic exploration, possibly due to the effect of translation of the original adjectives. In other words, the Turkish versions of these adjectives are not commonly used in relation to touch perception in Turkish language.

Experiment II

In order to explore the haptic information that is derived from visual exploration only we conducted Experiment II, in which the participants merely looked at the material and not touch it.

Participants

A different group of participants were included in experiment II. There were 30 participants in the only-vision behavioral experiment (18 female and 12 males). The age ranged between 19-36 and the average age was 22.43 years. Participants were university students in levels of undergraduate or postgraduate study. All participants had either intact vision or corrected vision with contact lenses/glasses. None of the participants had any visual impairments such as cataract or color-blindness etc.

All participants were given a written form describing the aim of the study. Each participant had signed a consent form and was informed their participation was voluntary and they were able to stop the experiment at any given point in case they feel disturbed for any reason. The participants were told they would receive 30 tl once the experiment was finished and they were paid after the experiment had finished. Each participant completed the experiment as one experiment lasting approximately ninety minutes.

Experimental Setup

The experimental setup in experiment II was identical to experiment I except that the cloth screen was removed and the table was moved to the wall. The participant was seated in front of the table and cannot see the remaining of items. One item in a glass container is put in front of him/her. The participant was able to see only one item at a time.

Stimuli

Materials and the adjective list used in the experiment II are identical as in the experiment I.

Procedure

One item in a glass container was placed in front of the participant on a black table by the experimenter. The participant was instructed merely to look at the respective item without touching or holding the container glass. The participant saw only the item that was in front of them, which was changed by the experimenter after the scoring of the list of adjectives for that particular material was finished. The room was illuminated in the same manner for all participants so that the visual information did not vary among the participants. While looking at the item, the participant was asked to score from 1 to 7 the same list of adjectives that is used in the previous behavioral experiment. Once the scoring of the complete list of adjectives is finished for the respective item, the experimenter changed the item in random order. Parameters such as timing, presentation manner, and auditory feedback in late responses were identical with the previous experiment.

Data Analysis

The same analyses as in the experiment I were conducted including consistency analysis, correlation analysis and Exploratory Factor Analysis with varimax rotation.

Results

Consistency analysis revealed good corrected item total correlation values, meaning that each of the participants' response per adjective correlated with all of the other participants' responses combined for the same adjective. Therefore, none of the participants were excluded in further analysis. Afterwards, we calculated Cronbach's alpha values for each adjective, as it can be observed in Table 6 the consistency analysis of vision data revealed excellent consistency per adjective among participants, Cronbach's alpha values varied among .841 and .989.

Table 6. Cronbach's alpha values for each adjective in the vision experiment

Adjective	Cronbach's Alpha	Adjective	Cronbach's Alpha
malleable	0,957	moisturous	0,978
leathery	0,94	woody	0,98
textured	0,928	glossy	0,974
elastic	0,971	scaly	0,971
inflexible	0,957	roughened	0,955
meaty	0,92	hard	0,985
compliant	0,914	slimy	0,979
doughy	0,98	spongy	0,97
delicate	0,841	granular	0,983
silky	0,964	airy	0,932
gelatinous	0,985	powdery	0,988
fluffy	0,945	hairy	0,985
scabby	0,977	gooey	0,981
velvety	0,973	sticky	0,983
slippery	0,957	soft	0,984
sandy	0,989		

An average of all participants' scores per each adjective was calculated and an Exploratory Factor Analysis with varimax rotation was conducted on these averaged scores. KMO and Barlett's tests were used to extract the factor loadings. For vision experiment the obtained KMO score was .613 and Barlett's test of sphericity was significant ($\chi2$ (465) = 1646.869 , p<0.001); suggesting that the data was appropriately distributed for Factor Analysis. Factor Analysis with varimax rotation as covariance based factor analysis with varimax rotation revealed eight factors in the vision data, explaining the 84 % of the variance in total, please see Fig.4 for the scree plot of the factor loadings.

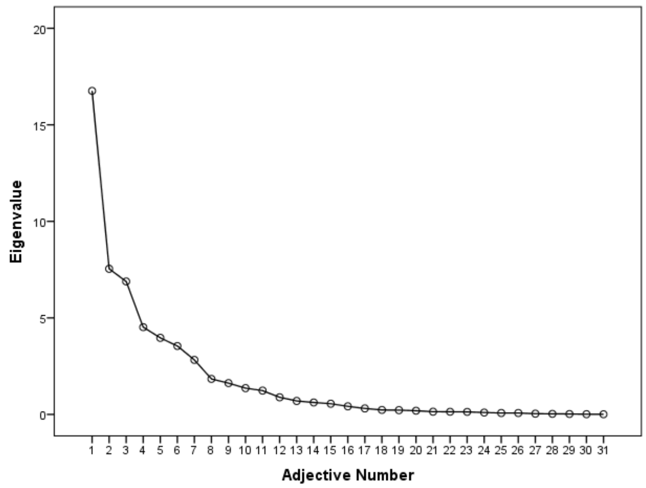


Figure 4. Scree plot of Factor Analysis for 31 adjectives in experiment II

In order to obtain a criterion value to determine factor loadings; communalities of adjectives is used as in the experiment I. Square root of 30% of the mean variance of the communalities is obtained as a criterion score; please see Table 7 for the criterion value. Each adjective above this cut-off value is highlighted with light grey in the Table 8. The adjectives that are highlighted with dark grey if the loadings is maximal across factors.

Table 7. Criterion value as square root of 30% of mean variance per adjective

Communalities	
malleable	1,954
leathery	0,576
textured	1,119
elastic	2,524
inflexible	2,456
meaty	0,300
compliant	1,176
doughy	2,093
delicate	1,202
silky	1,732
gelatinous	1,941
fluffy	1,143
scabby	1,384
velvety	1,910
slippery	1,363
sandy	2,902
moisturous	1,589
woody	1,861
glossy	2,074
scaly	1,429
roughened	1,749
hard	3,255
slimy	1,402
spongy	1,676
granular	3,473
airy	0,687
powdery	2,609
hairy	2,169
gooey	1,899
sticky	1,958
soft	3,388
Mean	1,83844
30% of Mean	0,551532
Sqrt of 30% of Mean	0,742652

Table 8. Factor loadings for experiment II

	Experiment II							
	Factor Loadings I-VI a,b							
	I.	II.	III	IV	V.	VI.	VII.	VIII.
	Deformability	Hairiness	Fluidity	Roughness	Granularity	Stickiness	Graininess	Surface Softness
compliant	0,963	0,048	0,1	-0,146	-0,045	-0,104	-0,15	0,086
malleable	1,17	0,24	0,302	-0,182	0,024	0,074	-0,054	0,094
elastic	1,319	0,558	0,176	-0,057	-0,106	0,05	-0,36	-0,174
inflexible	-1,29	-0,701	-0,233	0,137	0,178	0,019	0,185	0,01
doughy	1,139	-0,163	0,56	-0,208	0,075	0,071	-0,105	0,132
meaty	0,365	-0,082	0,099	-0,014	-0,033	-0,048	-0,144	0,002
delicate	0,56	0,491	0,231	-0,377	0,03	-0,149	0,046	0,012
fluffy	0,473	0,401	-0,007	-0,057	0,358	-0,18	0,057	-0,04
spongy	0,537	0,109	-0,37	0,099	0,519	-0,062	-0,03	-0,07
velvety	0,117	1,255	-0,203	0,041	0,179	-0,074	-0,236	0,169
silky	0,085	1,165	-0,117	-0,228	0,065	-0,08	-0,224	0,084
hard	-1,113	-1,192	-0,509	0,168	0,018	-0,005	-0,358	-0,031
leathery	0,123	0,45	-0,014	0,12	-0,084	-0,064	-0,214	-0,006
moisturous	0,222	0,046	1,133	-0,106	0,063	0,001	0,034	0,003
slimy	0,431	-0,078	1,048	-0,167	0,041	-0,024	-0,025	0,148
gelatinous	0,457	-0,123	1,233	-0,229	0,03	0,02	-0,082	0,161
slippery	0,09	0,068	0,929	-0,588	0,026	0,056	-0,236	0,051
glossy	-0,171	-0,104	0,471	-0,93	0,276	0,188	-0,068	0,274
roughened	-0,441	0,09	-0,343	0,851	0,122	-0,07	0,518	0,276
textured	-0,194	0,531	-0,262	0,67	0,11	-0,053	0,209	0,233
scabby	-0,314	-0,471	-0,14	0,743	-0,109	-0,047	0,195	-0,063
woody	-0,483	-0,715	-0,185	0,835	0,098	-0,089	-0,075	-0,03
granular	-0,115	0,014	0,035	-0,113	1,77	-0,063	0,026	-0,314
powdery	-0,12	0,019	0,26	-0,053	1,476	-0,041	-0,162	-0,202
gooey	0,011	-0,115	-0,051	-0,099	-0,075	1,314	0,07	0,124
sticky	-0,118	-0,134	0,087	-0,14	-0,035	1,234	-0,022	-0,166
sandy	-0,332	-0,358	-0,092	0,136	-0,094	0,011	1,573	0,069
scaly	-0,276	-0,267	-0,074	0,353	-0,087	0,027	0,971	-0,09
soft	-0,04	0,014	0,177	0,144	-0,323	0,893	-0,125	1,494
hairy	0,249	-0,158	0,153	-0,257	-0,325	-0,507	-0,08	1,109
airy	-0,012	0,256	0,066	0,038	-0,059	-0,037	0,063	0,466

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

a. Light gray if the loading is > 30% of the mean variance per adjective

b. Dark gray if the loading is > 30% of the mean variance per adjective *and* the loading is maximal among factors

In Table 8, the first factor explains 18.54% of variance. The adjectives “compliant”, “malleable”, “elastic”, “doughy”, and “inflexible” (negative loading) load together in this factor. *Deformability* may be used as a label for this factor loading.

The second factor explains 12.72% of the total variance. Adjectives observed in this factor loading are “velvety”, “silky” and “hard” (negative loading). Here, the material property *hairiness* seem to be effective. However, “hard” seems a little unusual among the other adjectives. Here, our guess is that “hard” is also loaded in this factor as a negative value as opposite to adjectives indicating hairiness, because the translation of hard (sert) may also be used as oppose to “smooth” in Turkish. This meaning nuance might have affected the responses.

The third factor explains 11.22% of variance. The loaded adjectives in this factor are “moisturous”, “slimy”, “gelatinous” and “slippery”. The material properties observed here, as a combination, are slipperiness, density and wetness and may be defined in one label of *fluidity*.

With a relatively lower loading, 7.67% of variance is explained by the fourth factor. Adjectives “glossy”, “roughened”, “scabby” and “woody” are loaded. Taken together, these adjectives seem to be related with the visual surface properties of the material, thus it can be said that *roughness* may explain this factor loading. “Glossy” has importance because it is an adjective that provides direct visual information and indirect haptic information such as the fact that probably the material is slippery or smooth in the surface.

The fifth factor loaded explains 10.83% of the variance. The adjectives “granular” and “powdery” load in this factor. These adjectives relate to the granularity of the material. Therefore we can say the material properties combination here is size and weight of the individual elements of the material of a granular substance; noting that it shall be a specific combination of small size and light weight. This combination may be defined as *granularity*.

The sixth factor explains 7.84 % of the variance and consists of adjectives “gooey” and “sticky”. These adjectives relates to the *stickiness* of the materials.

The seventh factor explains 7.73 % of the variance. Adjectives “sandy” and “scaly” are loaded. Sandy is an adjective that is used to define granular materials whereas scaly is used to define a grainy surface. Together, *graininess* might be suggested to explain this factor loading.

The last and eighth factor explains 7.44% of the total variance in data. Adjectives “soft” and “hairy” are loaded. These adjectives relate to the *surface smoothness* perception. Therefore we can say surface softness may explain this factor loading.

Discussion

Eight factors were loaded in the vision experiment. The first factor explains 18.54 % and the second factor explains 12.72 % of variance. Here, with comparison to the haptic experiment; it seems that the number of factors are high but each factor explains relatively less of total variance. For the visual experiment, adjectives meaty, delicate, fluffy, spongy, leathery, textured, and airy did not load in any factor. It might be argued that these adjectives were not suitable for a visual exploration. Probably the translated versions of these adjectives were not used often in Turkish language when expressing a visual perception.

Experiment I and II Comparison

Comparing experiment I and experiment II, we found that mostly the same adjectives loaded together. In Table 9 for a comparison of the loaded factors in each experiment and the corresponding adjectives in each factor may be seen.

Table 9. Comparison of the factor loadings and corresponding adjectives in the haptic and vision experiments

Experiment I (haptic only)	Factor	Experiment II (vision only)	Factor
compliant, delicate, elastic, hard, inflexible, malleable, soft, spongy	deformability	compliant, doughy, elastic, inflexible, malleable, *hard*	deformability
gelatinous, gooey, moisturous, slimy, sticky, *doughy, soft*	fluidity	gelatinous, moisturous, slimy, slippery	fluidity
		gooey, sticky, *soft*	stickiness
hairy, silky, velvety, *hard*	hairiness	hard, silky, velvety	hairiness
		hairy, soft	surface softness
granular, powdery, sandy, scaly	granularity	granular, powdery	granularity
		sandy, scaly	graininess
glossy, roughened, slippery, textured	roughness	glossy, roughened, scabby, woody	roughness
doughy	density	-	-

As it may be clearly observed, the eight factor loadings in the vision experiment correspond to the six factors loaded in the haptic experiment. There are 2 factor loadings in the vision experiment that are different from the haptic experiment. Although the adjectives gooey and sticky loaded together with the other adjectives in the haptic experiment; in the vision experiment they are loaded as a separate factor, which is labeled as stickiness. Again, adjectives sandy and scaly were loaded with other similar adjectives in the haptic experiment whereas they constitute an independent factor in the vision experiment, which is defined as graininess. This correspondence show that some of the haptic factors correspond one-to-one to visual factors whereas some haptic factors split into two visual factors.

When the factor loadings of the two experiments are visually compared (see Table 10), it is observed that overall the structures of the haptic and vision experiments are similar. Although the number of factors in the haptic experiment are less, they seem to load higher than the factors in the vision experiment. It might signify that more than one factor loading are combined in the haptic experiment, which means some material properties are perceived in the same category by haptic exploration; whereas the differentiation of material properties by vision is better because more factor loadings are obtained, meaning that different material properties are not grouped together.

Table 10. Factor loadings from experiment I and II side by side for visual interpretation

	Experiment I					
	I	II	III	IV	V	VI
	Deformability	Fluidity	Hairiness	Granularity	Roughness	Density
airy	0,062	-0,054	0,559	0,197	-0,091	0,002
compliant	0,843	-0,009	-0,205	-0,37	-0,137	0,114
delicate	0,862	0,159	0,235	-0,143	-0,178	-0,162
doughy	0,615	0,857	-0,036	-0,001	-0,081	0,876
elastic	1,388	0,217	0,056	-0,411	0,008	0,615
fluffy	0,671	0,099	0,192	-0,076	0,504	-0,07
gelatinous	0,454	1,246	-0,165	-0,162	-0,252	0,162
glossy	-0,049	0,171	-0,092	-0,304	-0,747	-0,383
gooey	0,264	1,453	-0,025	-0,026	-0,211	0,227
granular	-0,238	-0,345	-0,475	1,608	0,3	-0,613
hairy	0,103	-0,093	1,045	-0,134	0,389	0,04
hard	-1,468	-0,611	-0,809	-0,015	-0,116	-0,175
inflexible	-1,41	-0,3	-0,256	0,255	-0,127	-0,465
leathery	0,21	-0,039	0,37	-0,193	-0,014	0,327
malleable	0,834	0,373	-0,007	-0,104	-0,085	0,448
meaty	0,191	0,266	-0,037	-0,046	0,026	0,535
moisturous	0,129	1,195	-0,052	-0,03	-0,222	0,05
powdery	-0,291	0,001	0,173	1,544	0,081	0,125
roughened	-0,157	-0,563	-0,09	0,475	1,091	-0,471
sandy	-0,321	-0,05	-0,034	1,565	0,085	-0,057
scabby	-0,367	-0,134	-0,327	0,201	0,381	-0,112
scaly	-0,347	-0,078	-0,109	0,82	0,515	0,053
silky	0,278	-0,049	0,828	-0,107	-0,137	-0,141
slimy	0,261	1,181	-0,123	-0,12	-0,193	0,13
slippery	0,021	0,621	0,169	-0,269	-0,814	-0,309
soft	1,461	0,735	0,685	-0,224	-0,026	0,047
spongy	0,903	-0,077	0,245	-0,204	0,645	0,015
sticky	0,113	1,303	-0,064	0,001	-0,201	0,094
textured	0,016	-0,333	0,343	0,005	0,861	-0,169
velvety	0,226	-0,161	1,171	-0,131	0,345	0,048
woody	-0,686	-0,197	-0,384	-0,015	0,334	-0,112

	Experiment II							
	I.	II.	III	IV	V.	VI.	VII.	VIII.
	Deformability	Hairiness	Fluidity	Roughness	Granularity	Stickiness	Graininess	Surface Softness
airy	-0,012	0,256	0,066	0,038	-0,059	-0,037	0,063	0,466
compliant	0,963	0,048	0,1	-0,146	-0,045	-0,104	-0,15	0,086
delicate	0,56	0,491	0,231	-0,377	0,03	-0,149	0,046	0,012
doughy	1,139	-0,163	0,56	-0,208	0,075	0,071	-0,105	0,132
elastic	1,319	0,558	0,176	-0,057	-0,106	0,05	-0,36	-0,174
fluffy	0,473	0,401	-0,007	-0,057	0,358	-0,18	0,057	-0,04
gelatinous	0,457	-0,123	1,233	-0,229	0,03	0,02	-0,082	0,161
glossy	-0,171	-0,104	0,471	-0,93	0,276	0,188	-0,068	0,274
gooey	0,011	-0,115	-0,051	-0,099	-0,075	1,314	0,07	0,124
granular	-0,115	0,014	0,035	-0,113	1,77	-0,063	0,026	-0,314
hairy	0,249	-0,158	0,153	-0,257	-0,325	-0,507	-0,08	1,109
hard	-1,113	-1,192	-0,509	0,168	0,018	-0,005	-0,358	-0,031
inflexible	-1,29	-0,701	-0,233	0,137	0,178	0,019	0,185	0,01
leathery	0,123	0,45	-0,014	0,12	-0,084	-0,064	-0,214	-0,006
malleable	1,17	0,24	0,302	-0,182	0,024	0,074	-0,054	0,094
meaty	0,365	-0,082	0,099	-0,014	-0,033	-0,048	-0,144	0,002
moisturous	0,222	0,046	1,133	-0,106	0,063	0,001	0,034	0,003
powdery	-0,12	0,019	0,26	-0,053	1,476	-0,041	-0,162	-0,202
roughened	-0,441	0,09	-0,343	0,851	0,122	-0,07	0,518	0,276
sandy	-0,332	-0,358	-0,092	0,136	-0,094	0,011	1,573	0,069
scabby	-0,314	-0,471	-0,14	0,743	-0,109	-0,047	0,195	-0,063
scaly	-0,276	-0,267	-0,074	0,353	-0,087	0,027	0,971	-0,09
silky	0,085	1,165	-0,117	-0,228	0,065	-0,08	-0,224	0,084
slimy	0,431	-0,078	1,048	-0,167	0,041	-0,024	-0,025	0,148
slippery	0,09	0,068	0,929	-0,588	0,026	0,056	-0,236	0,051
soft	-0,04	0,014	0,177	0,144	-0,323	0,893	-0,125	1,494
spongy	0,537	0,109	-0,37	0,099	0,519	-0,062	-0,03	-0,07
sticky	-0,118	-0,134	0,087	-0,14	-0,035	1,234	-0,022	-0,166
textured	-0,194	0,531	-0,262	0,67	0,11	-0,053	0,209	0,233
velvety	0,117	1,255	-0,203	0,041	0,179	-0,074	-0,236	0,169
woody	-0,483	-0,715	-0,185	0,835	0,098	-0,089	-0,075	-0,03

Table 11 shows the absolute values of the average scores for each common factor across experiments. The average scores are similar, this means that the factor structure between the experiments are alike and it may signify that similar material properties regarding touch perception can be derived from both merely haptic information and merely visual information.

Table 11. The average scores and ranges of common factor loadings between experiments

		Average		Minimum and Maximum Factor Loading Value				Range	
		Experiment I	Experiment II	Experiment I		Experiment II		Experiment I	Experiment II
Factor I	Deformability	0,147452	0,106194	-1,468	1,461	-1,29	1,319	2,929	2,609
Factor II	Fluidity	0,218839	0,143871	-0,611	1,453	-0,509	1,233	2,064	1,742
Factor III	Hairiness	0,08971	0,03529	-0,809	1,171	-1,192	1,255	1,98	2,447
Factor IV	Granularity	0,115677	0,13171	-0,411	1,608	-0,325	1,77	2,019	2,095
Factor V	Roughness	0,062355	0,012387	-0,814	1,091	-0,93	0,851	1,905	1,781

Another important point in Table 11 is the range of the factor loadings. The ranges of factor loadings seem similar in general, however; hairiness has relatively narrower ranges in experiment I when compared to experiment II. This difference means that these factors have less perceptual frequency; in other words, participants were able to recognize the gradual differences of material properties regarding hairiness better when they see the material as compared to when they touch it. On the other hand, in general, the ranges of haptic factors are greater than visual factors. This means the gradual differences might be better detected haptically than visually.

Factor Analysis on the combined data from Experiment I and II

Upon obtaining the result that the ranges and averages of the two experiments correspond to each other we performed another exploratory factor analysis with varimax rotation on combined data from the two experiments with Barlett’s variables in order to see if the factor loadings resemble to the separate factor loadings in the experiment I and experiment II. This factor analysis included Barlett’s scores as overall factor loadings. This analysis provided the information of factor loadings corresponding to each material within the complete data from both experiments (please see Fig 5).

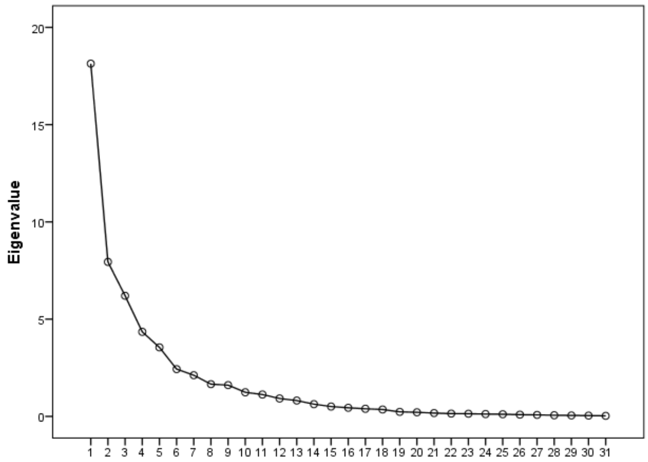


Figure 5. Scree plot of Factor Analysis for 31 adjectives in the combined dataset

The motivation for conducting a factor analysis on the combined data was that, in case the factor loadings were exactly same as the two separate experiments, it would mean that there was not a difference of contribution of the haptic and visual domains. In case that we obtained factors that seemed to be combined (for instance a factor explaining both roughness and granularity at the same time), it would mean that actually vision and haptics contributed differently and that would be the reason we obtained combined factors in the combined.

The same method to determine a criterion value for factor loadings as in the experiment I and II is used. Square root of 30% of the mean variance of the communalities is obtained as a criterion score; please see Table 12 for the criterion value. Each adjective above this cut-off value is highlighted with light grey in Table 13. The adjectives are highlighted with dark grey if the loadings is maximal across factors. Again, covariance based factor analysis with varimax rotation was performed in the same manner as in Experiment I and II.

Table 12. Criterion value as square root of 30% of mean variance per adjective

Communalities

	Raw	
	Initial	Extraction
malleable	1,724	1,251
leathery	,546	,234
textured	1,162	,810
elastic	2,607	2,346
inflexible	2,546	2,365
meaty	,412	,201
compliant	1,126	,842
doughy	2,124	1,661
delicate	1,193	,732
silky	1,361	1,150
gelatinous	1,966	1,727
fluffy	1,222	,664
scabby	1,034	,626
velvety	1,824	1,497
slippery	1,342	1,191
sandy	2,815	2,557
moisturous	1,560	1,151
woody	1,513	1,012
glossy	1,746	,896
scaly	1,463	1,115
roughened	1,997	1,523
hard	3,341	3,110
slimy	1,484	1,278
spongy	1,706	1,098
granular	3,535	3,251
airy	,677	,293
powdery	2,651	2,257
hairy	1,846	1,470
gooey	2,096	1,912
sticky	1,929	1,669
soft	3,339	2,832
Mean	1,803	
30% of Mean	0,541	
Sqrt of 30% of Mean	0,735	

Table 13. Factor loadings on combined data from experiment I and II

	Factor Loadings a,b						
	I.Deformability	II. Roughness & Fluidity	III. Surface Softness & Hairiness	IV.Stickiness	V.Granularity	VI.Roughness & Granularity	VII.Hairiness
elastic	1,374	-0,004	0,515	0,094	-0,239	-0,329	-0,141
inflexible	-1,346	0,026	-0,685	-0,119	0,23	0,129	-0,021
malleable	1,048	0,225	0,285	0,124	-0,064	-0,018	-0,012
compliant	0,841	0,112	0,114	-0,097	-0,169	-0,267	0,01
doughy	1,141	0,482	-0,096	0,323	0,031	0,017	0,11
hard	-1,244	-0,057	-1,159	-0,316	-0,005	-0,223	-0,259
meaty	0,418	0,104	-0,076	0,063	-0,075	-0,014	-0,012
delicate	0,602	0,218	0,54	-0,01	0,009	-0,105	0,139
fluffy	0,581	-0,238	0,232	-0,028	0,293	-0,262	0,249
spongy	0,635	-0,549	0,156	0,056	0,296	-0,493	0,189
slippery	0,085	1,039	0,197	0,186	-0,012	-0,125	0,122
textured	-0,123	-0,8	0,247	-0,046	0,081	0,036	0,291
roughened	-0,343	-1,023	-0,227	-0,138	0,292	0,319	0,317
glossy	-0,197	0,867	0,08	0,056	0,09	-0,281	0,096
slimy	0,616	0,79	-0,122	0,45	0,028	0,124	0,201
gelatinous	0,741	0,904	-0,158	0,511	0,038	0,048	0,265
moisturous	0,452	0,804	-0,06	0,48	0,113	0,164	0,164
silky	0,01	-0,012	1,039	-0,037	0,031	-0,214	0,149
velvety	0,058	-0,352	1,084	-0,064	0,085	-0,243	0,352
woody	-0,491	-0,363	-0,791	-0,104	0,034	-0,026	0,025
scabby	-0,275	-0,42	-0,568	-0,038	-0,009	0,225	0,015
leathery	0,188	-0,08	0,387	-0,044	-0,188	-0,064	0,023
gooey	0,192	0,32	-0,039	1,324	-0,086	0,021	-0,107
sticky	0,044	0,36	-0,028	1,211	-0,047	0,057	-0,254
soft	0,491	-0,026	0,393	1,099	-0,342	-0,21	1,033
granular	-0,244	-0,161	-0,149	-0,215	1,723	0,22	-0,281
powdery	-0,127	0,062	0,023	-0,034	1,466	0,285	-0,065
sandy	-0,335	-0,29	-0,228	0,062	0,453	1,447	0,079
scaly	-0,215	-0,448	-0,326	0,028	0,238	0,839	0,016
hairy	0,118	0,034	0,239	-0,256	-0,212	-0,038	1,134
airy	-0,049	0,004	0,354	-0,008	0,012	0,156	0,375

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 8 iterations.

a. Light gray if the loading is > 30% of the mean variance per adjective

b. Dark gray if the loading is > 30% of the mean variance per adjective *and* the loading is maximal among factors

The factor loadings in the combined dataset resemble the separate factor loadings of experiment I and II. The difference here is that, some material properties are loaded together as one factor.

For instance, the second factor loading can be labelled as roughness and fluidity as it includes both adjectives that are related to roughness such as textured and roughened and also to fluidity such as slimy, moisturous. Similarly, the third factor seems to be several separate factors that we observed in experiment I or II loaded as one factor; adjectives silky and velvety are related to hairiness and adjectives woody and hard are related to surface softness (negative loadings); therefore this factor is labeled as surface softness & hairiness. Other than these; when the combined data is examined, the factor loading structure seems similar to the separate results from experiment I and experiment II.

The most significant aspect of the study is to compare the factor loadings in the two experiments in order to explain i) what the dimensions of softness in haptic domain are and ii) what kind of haptic information is derived from visual information. Consequently, in addition to the general comparisons provided above; a more detailed comparison of the factor loadings on the combined dataset obtained from both of the experiments is performed. In the figures below, different factor loadings per material can be observed as a comparison across haptic and visual experiments.

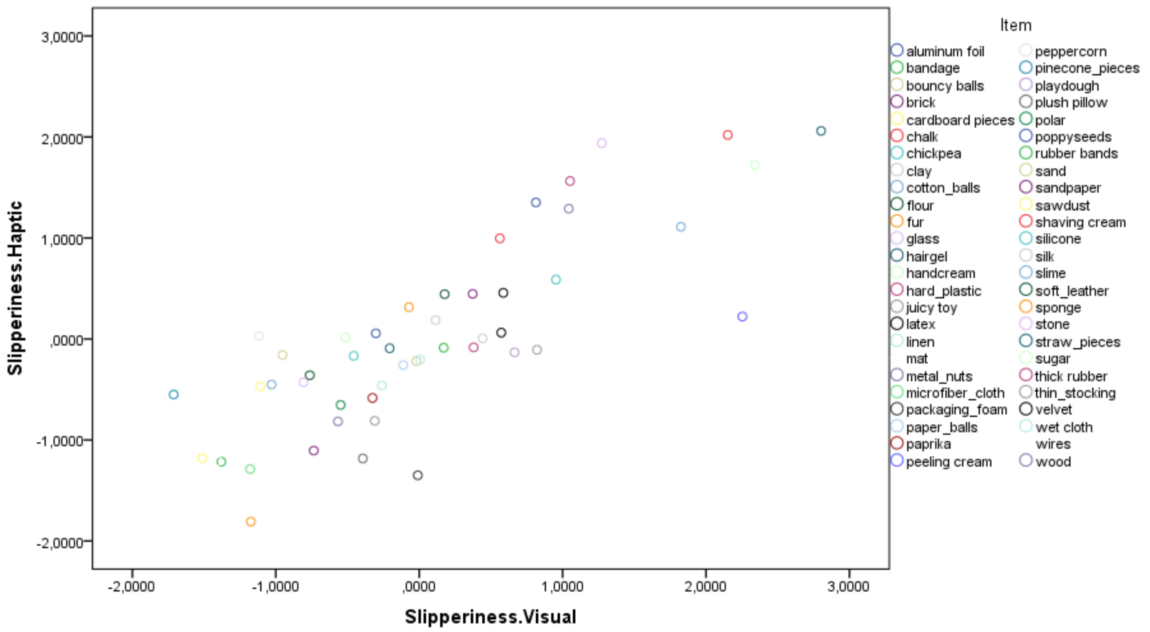


Figure 6. Slipperiness factor loading per material across haptic and visual experiments

Figure 6 depicts the slipperiness factor across haptic and visual experiments. As it can be observed, none of the materials had very high factor loadings in visual and had low factor loadings in haptic exploration and vice versa. Overall, this signifies that none of the materials were rated very slippery in one domain while they were being rated non-slippery in the other domain. The factor loadings across the experiments fall into a diagonal axis. This means, one domain for judging the slipperiness of an item with one exploration type provided more or less the same amount of information as the other exploration type did. Of course there were differences between the materials. For instance, hair gel was rated as very slippery in both haptic and visual experiments whereas sawdust was rated very low in slipperiness in both experiments. These discrepancies are due to the varying range of slipperiness that different materials have. Thus, overall, it can be said that for slipperiness dimension, no difference between the haptic exploration and visual exploration was observed, since the correlation between the experiments was statistically significant (r=.797, *p=.000*).

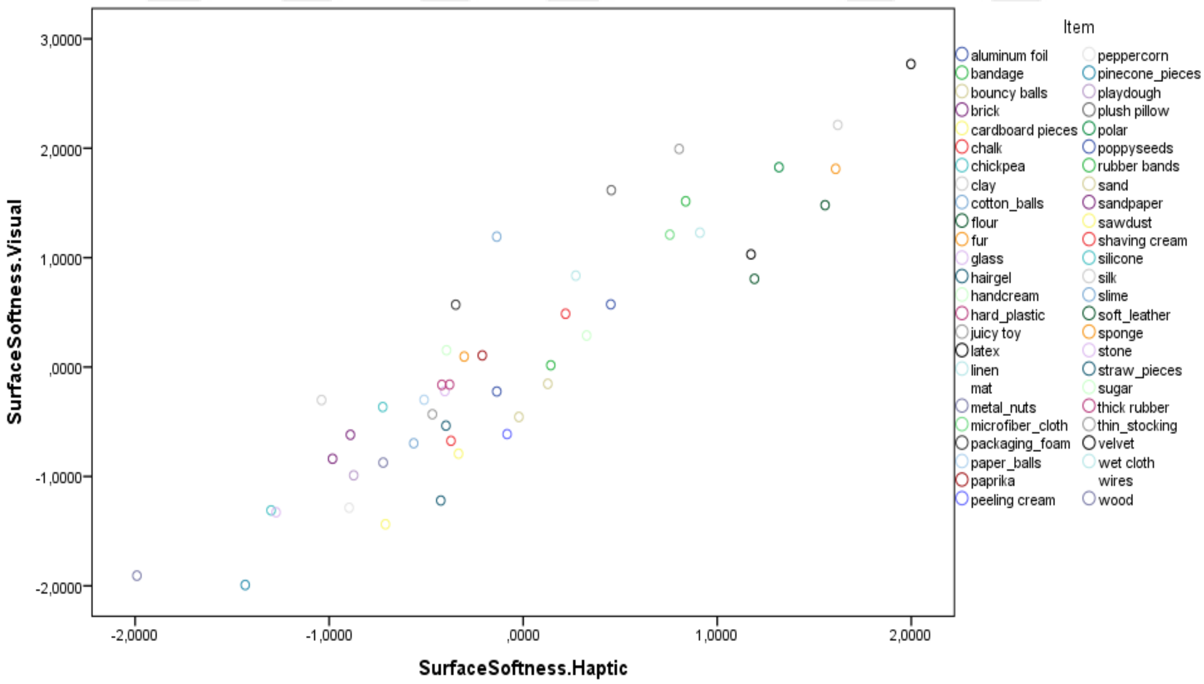


Figure 7. Surface softness factor loading per material across haptic and visual experiments

Figure 7 depicts the surface softness factor across haptic and visual experiments. As it can be observed, none of the materials had very high factor loadings in visual and had low factor loadings in haptic exploration and vice versa. Again, the distribution of the data is diagonal, meaning one item that had a rating of surface softness in one domain obtained a similar rating of surface softness in the other domain. Material differences are observed due to the varying amounts of surface softness each material has: velvet for example, had the greatest surface softness ratings in both experiments whereas pinecone pieces had the lowest surface softness ratings across the experiments. Overall, it can be said that for the surface softness dimension, no difference between the haptic exploration and visual exploration was observed, because the correlation between the experiments was statistically significant (r=.911, *p=.000).*

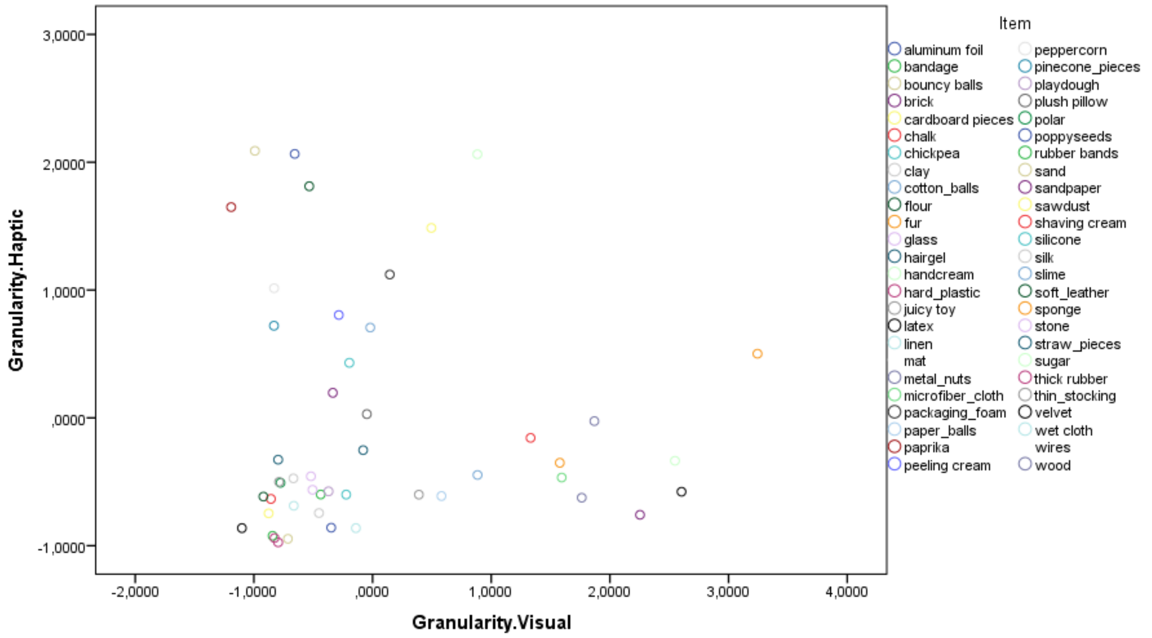


Figure 8. Granularity factor loading per material across haptic and visual experiments

Figure 8 depicts the granularity factor across haptic and visual experiments. Here the distribution is not diagonal and some materials had high granularity ratings in haptic and had low granularity ratings in visual experiment while the case is vice versa for some other materials. For instance, sponge, brick and hand cream are rated as more granular when explored visually compared to being haptically explored. On the other hand, flour, paprika and peppercorn are rated more granular when explored haptically. This means that, the materials that are more granular in their nature were rated more granular by touch while the materials that are moderately granular were perceived very granular by vision. It can be said that there was a statistically significant difference between the experiments; as the correlation between the experiments was not significant (r=-.047, $p > .05$).

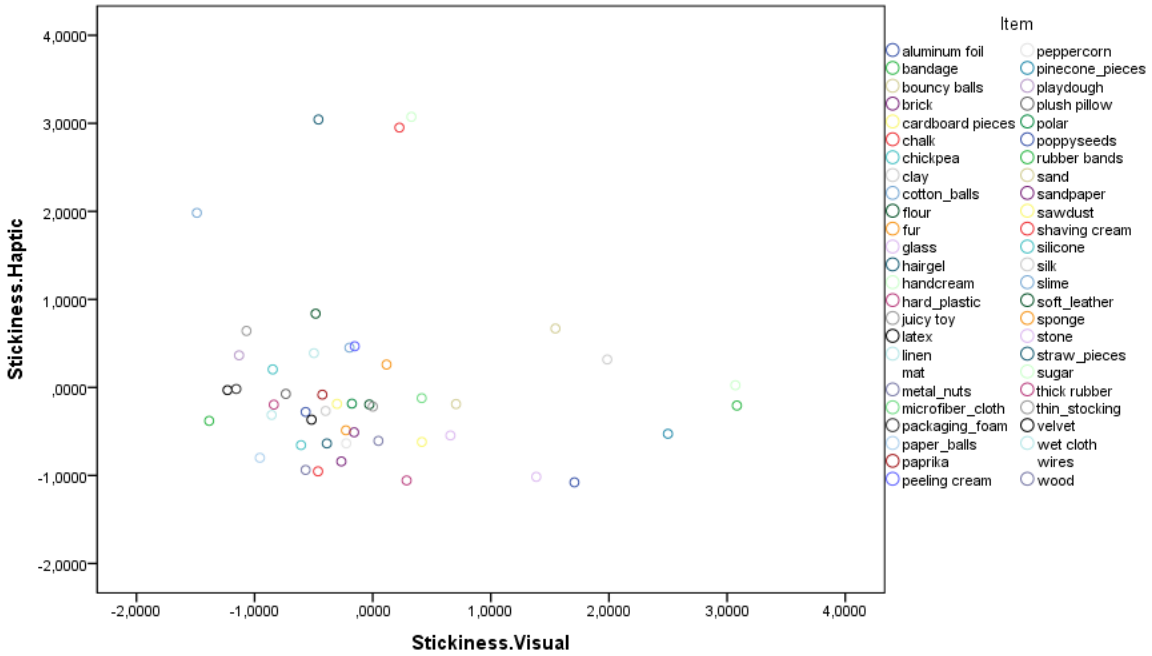


Figure 9. Stickiness factor loading per material across haptic and visual experiments

Figure 9 depicts the stickiness factor across haptic and visual experiments. Again the distribution is not diagonal and some materials had high stickiness ratings in one domain and had low stickiness ratings in the other domain. Sugar, pinecone pieces, bandage had higher stickiness ratings in visual experiment whereas hair gel, hand cream, shaving cream, slime had higher stickiness ratings in the haptic experiment. Overall it can be said that the materials that had medium stickiness were rated stickier when explored by vision and the materials that had high stickiness were rated stickier by haptic exploration. As a result, it can be said that there was a statistically significant difference between the experiments regarding stickiness ratings, since the correlation between the experiments was not significant (r=-.099, $p > .05$).

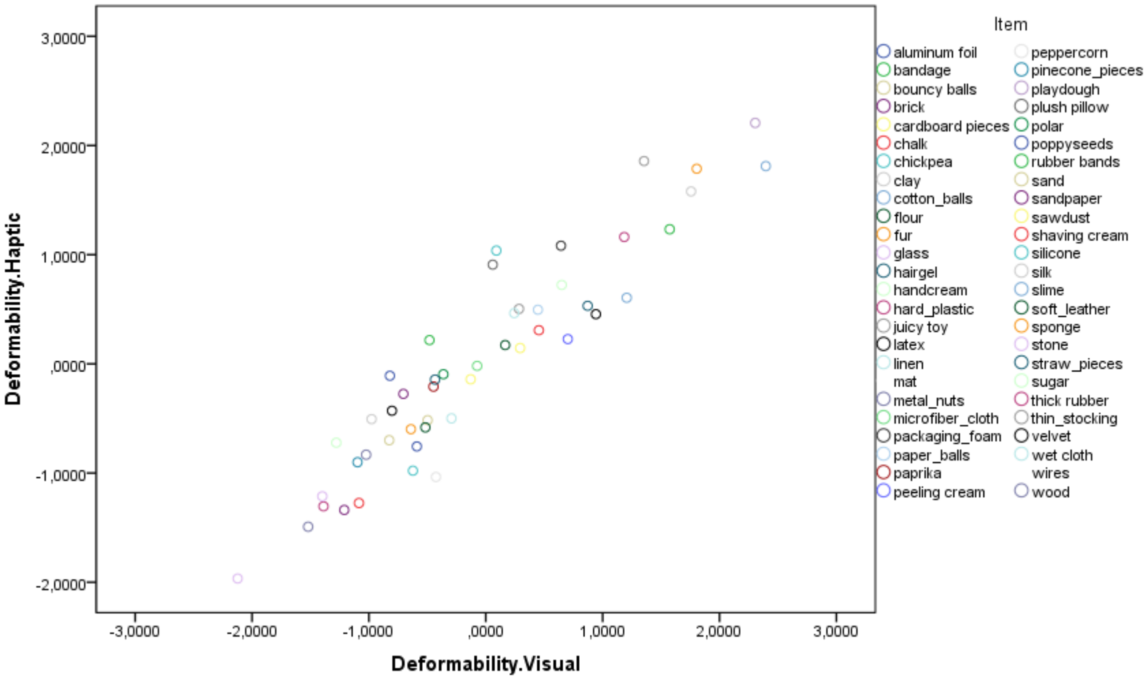


Figure 10. Deformability factor loading per material across haptic and visual experiments

Figure 10 depicts the deformability factor across haptic and visual experiments. The overall distribution is diagonal, signifying that haptic domain for judging the deformability of an item provided more or less the same amount of information as the vision domain did. A difference between the materials occurred naturally; for instance playdough and slime were rated very deformable in both experiments and glass was rated as very non-deformable in both experiments. This difference again is due to difference of the deformability across the materials and no difference was observed across haptic and visual exploration. In other words, the correlation of scores between the experiments was significant (r=.923, $p=.000$); therefore there was no difference between the information haptic or visual exploration provided.

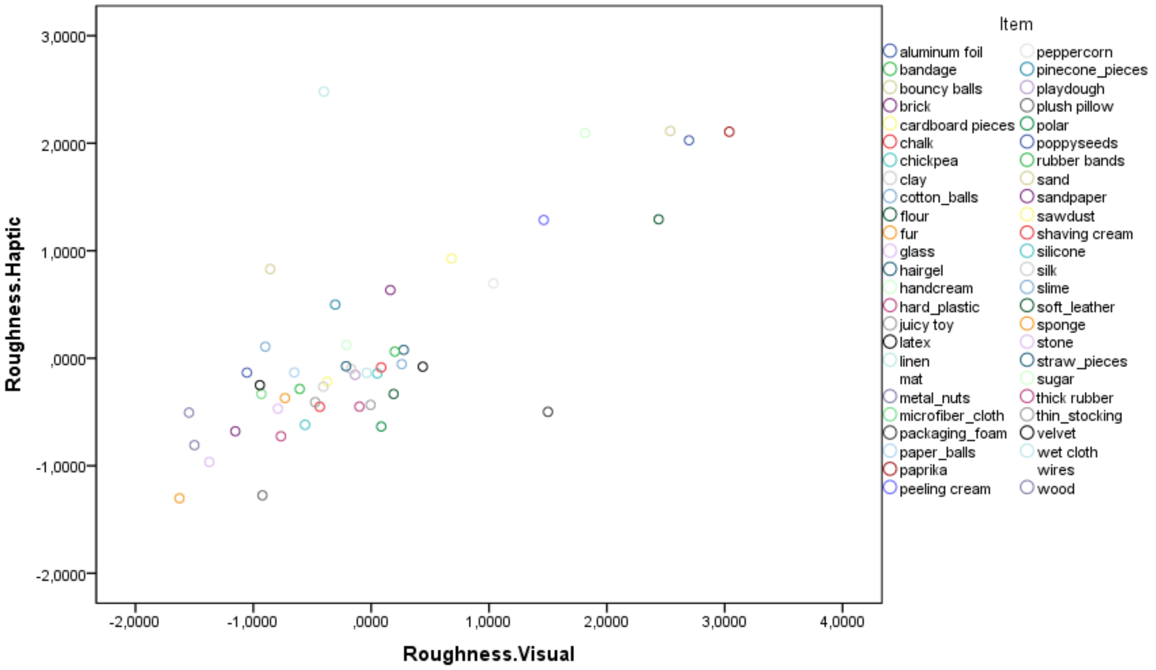


Figure 11. Roughness factor loading per material across haptic and visual experiments

Figure 11 depicts the roughness factor across haptic and visual experiments. Generally the distribution is diagonal, meaning roughness scores each item had were similar across the experiments. However, there are exceptions; packaging foam was rated rougher in the visual experiment compared to the haptic experiment and wet cloth was rated rougher in the haptic experiment compared to the visual experiment. Overall, it can be said that there is a statistically significant correlation between the experiments (r=.752, *p=.000*); therefore no difference between the experiments has been observed.

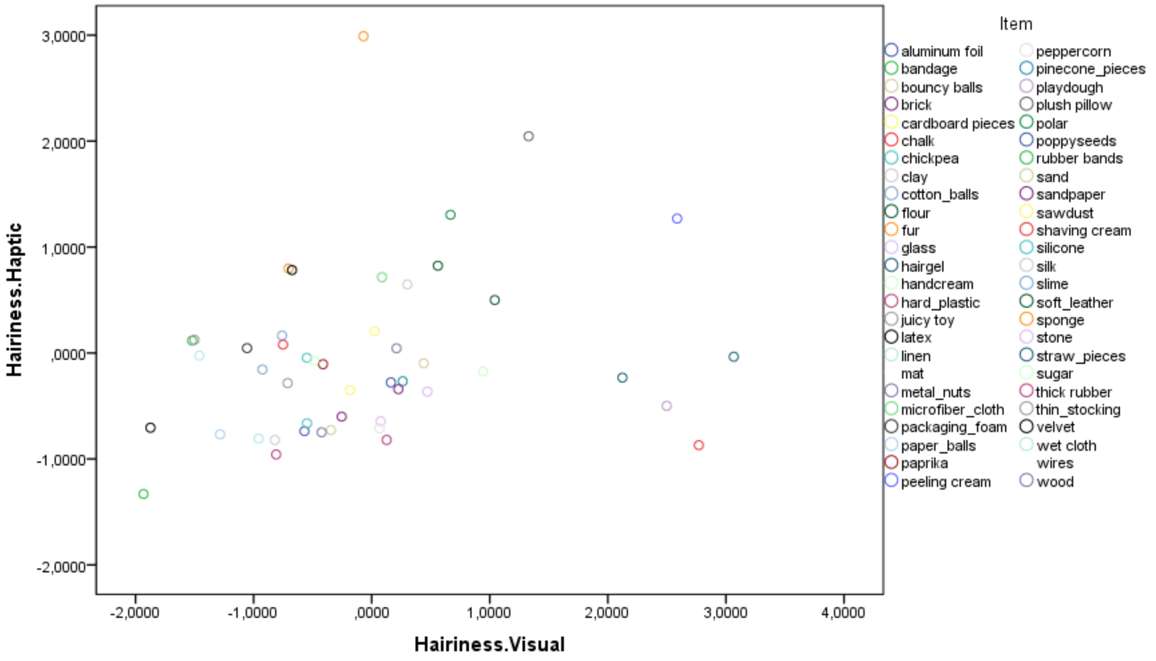


Figure 12. Hairiness factor loading per material across haptic and visual experiments

Figure 12 depicts the hairiness factor across haptic and visual experiments. The overall distribution is not diagonal, signifying that haptic and visual domains for judging the hairiness of an item provided different information. Fur was clearly rated more hairy in the haptic experiment as compared to vision and chalk, flour, hair gel, playdough and were judged as hairier in the visual experiment as compared to the haptic experiment. As a result it can be said that there is not a statistically significant correlation between the ratings across experiments (r=.266, p >*.05*). In other words, haptic and visual information contributed differently to the perception.

Chapter 3

General Discussion

The two main goals of the study was to explore the haptic dimensions of perceived softness and to investigate the haptic information derived from vision only. Previous haptic studies on softness perception considered softness as an equivalent to compliance. Our results suggest that softness has more dimensions than only compliance. We also found that haptic and visual explorations provide different information regarding some of these dimensions.

The factor analysis performed on the combined data set revealed that the structure is similar to the results of separate factor analysis on the haptic and visual experiments. This suggests that groups of adjectives load on similar factors for separate experiments and also in the combined dataset; meaning that the experimental design was internally consistent. Also, it means that the vision and haptic information provide information in a similar manner to the haptic perception.

The Figures 6-12 are especially important since they depict whether or not there was a difference between the factor loadings per material across haptic and visual experiment. As Figures 6,7, 10 and 11 show, the factor loadings of slipperiness, softness, deformability and roughness did not vary across haptic or visual experiments. Put differently, haptic exploration and visual exploration provide a similar amount of information for these factor loadings. The direct haptic information, as we refer in the present paper, from touch is very similar to the inferred or derived haptic information from vision.

Nevertheless, as Figures 8, 9 and 12 illustrate, a difference is observed across the experiments regarding factor loadings per material for granularity, stickiness and hairiness. This means that haptic exploration and visual exploration provided different information shaping the resulting perception. Overall, if the material property highly applied to the material, its haptic loadings were higher. If the material property moderately applied to the material, its visual loadings were higher. To further elucidate, for instance, flour, paprika and peppercorn were rated more granular haptically; sponge and brick, hand cream were rated more granular visually. Materials that have high granularity as their material property (flour, paprika, and peppercorn) benefited more from haptic exploration. On the other hand, vision enhanced the granularity scores for materials that are moderately granular (sponge, brick, and hand cream). A similar case occurred with stickiness and hairiness. Materials that have high stickiness as their material property (hair gel, hand cream, having cream, slime) had high stickiness ratings in the haptic exploration; whereas vision enhanced the stickiness scores for materials that are moderately sticky (sugar, pinecone pieces, bandage). Again, for the hairiness factor loading, materials with high hairiness as its material property (fur) had high scores in haptic experiment while vision enhanced the hairiness scores for materials that are moderately hairy (chalk, flour, hair gel, playdough). This is an interesting finding suggesting that vision might play an enhancer role for some of the haptic material properties including granularity, stickiness and hairiness. In other words, some of the haptic properties of materials are derived from visual information in an enhanced manner; we visually perceive a moderately granular or sticky or hairy item more granular or stickier or hairier than we would have perceived by touch. This difference between the haptic and visual exploration is the most significant finding of the study. Our finding seems to support finding of Drewing et.al. (2009) that some materials looked softer than they felt. Their study focused only on softness whereas we mapped different dimensions of softness and the effect of vision on these dimensions. It can be suggested that this “enhancer” effect of vision not only apply to general softness perception, but also to a group of different material properties composed of granularity, stickiness and hairiness.

The amount of contribution of haptic and visual information to haptic perception has been an issue of debate. Srinivasan (1999) investigated the weights of the visual and haptic input into the final perception. When participants were presented with incongruent visual and haptic information on a surface displacement task, vision modality was found to be dominating the haptic information. However, the haptic perception became more accurate when both types of information were provided simultaneously. This shows that the weight of the modalities vary depending on the circumstances and vision dominates haptic experience in particular cases when judging virtual surface stimuli. Contrary to this, Drewing et al. (2009) hypothesized that such a dominance of vision would not be expected with natural stimuli and this previously observed dominance of vision might have been due to the fact that the stimuli was virtual. They based the idea on the fact that the exploration procedure provided only the kineasthetic cues whereas natural stimuli would require more of cutaneous information rather than the kineasthetic ones and since the former plays a more significant role in haptic information, no such dominance would be observed. It is also suggested (Cellini et al., 2013) that another factor for such a greater weight of vision effect over haptics would arise from the stimuli being artificial. They argued that it is a possibility that the artificial stimuli might have resulted in the easier visual detectability of the surface formation, since the materials had high compliance and such bias would not be observed with natural material due to the high variability of the visual and compliance combinations of the materials. Indeed, the same study showed evidence supporting this hypothesis. They investigated how the indirect visual cues are used for the softness perception of deformable surfaces and how it is integrated with the haptic information. They used two rubber stimuli with much lower compliance values compared to the previous studies with virtual stimuli. Here, unlike previous results, vision did not govern the haptic modality and even haptic information slightly dominated vision. This once again shows that the weights of the two modalities may change depending on the experimental setup and vision and haptic do not contribute equally to the perception. The findings of these cue conflict studies are in compliance with our findings that vision provides information that is different than the haptics provide in different circumstances, in our case when judging granularity, stickiness and hairiness. On the other hand, we did not find a difference between the information haptics and vision provide on the judgment of slipperiness, softness, deformability and roughness. Again, the results of the cue-conflict studies are in compliance with this finding because we know that depending on the circumstances including stimuli type, experimental setup and touch procedure, haptics and vision may provide information in a very similar manner.

Why Softness as a Focus?

In haptic literature, some of the material properties were consistent across many studies: roughness/smoothness (macro, uneven or relief; micro, rough/smooth), hardness/softness, coldness/warmness. Nevertheless some material properties were focused on by only a few number of studies and revealed less consistent results of perception; such as moistness/dryness (friction) and stickiness/slipperiness (friction) (Okamoto, Nagano, & Yamada, 2012). In a review, from eighteen studies of touch perception, Okamoto et al. summarized five main dimensions of touch: macro and micro roughness, warmness, hardness and friction (moistness and slipperiness). Out of these categories, "roughness" and "softness" seemed to have greater use in the touch perception (Guest et al., 2012). Roughness is the most studied aspect of the perceptual factors affecting the tactile investigation in the literature (Chen, X., Shao, F., Barnes, C., Childs, T., & Henson, 2009). Softness has been studied very rarely and it was studied by focusing on compliance (Drewing, Ramisch, & Bayer, 2009) and its dimensionalities has not been investigated in the previous literature. The present paper fills this gap in the literature.

Limitations

Studying haptics and vision separately

Although haptic studies that do not require the participants to combine visual and haptic domains provide significant information regarding touch perception, they lack some information about the material perception that we experience daily, as the haptic material perception is actually an intermodal process (Baumgartner, Wiebel, & Gegenfurtner, 2013) occurring by a complex reciprocal mechanism including both vision and haptics. The majority of the studies between 1968 and 2011 mainly focused on the haptic perception as an individual concept separate from vision perception (Okamoto et al., 2012) and overlooked the intermodality of the experience. Although the present study aims to understand the haptic information that is derived from the visual experience; our design required participants to use either haptic or visual information, not both simultaneously. This procedure provides us controlled data without any confounding variable; however, it must be admitted that our design, like the previous studies stated above, is quite different than what we experience in daily life. When we interact daily with materials, often we receive both visual and haptic inputs simultaneously and a reciprocal feedback mechanism probably occurs between the two modalities. This information flow is expected to have an effect on the resulting perception, which we avoided in our design. Future studies shall have designs that are closer to our daily life experience in order to shed light upon a possible reciprocal mechanism between the haptic and visual systems.

Associative Effects of Prior Knowledge

One possibility is that there might be long term memory effects in our design; in other words, in haptic or vision experiments, if the participant recognized the item from previous experience, there might be associations with it that come from previous experience. Although the participants were specifically instructed to ignore the previous experience, unconscious associations might occur and play a role effecting the ratings. To avoid such effect, we randomized the presentation of materials for each participant and the presentation of adjectives for each material and aimed for at least 30 participants for each experiment. Therefore, if any association occurred for a particular participant, a different association would occur for another participant and a possible bias would be cancelled out in the complete dataset. Still, in order to control the possible associations, one procedure that might be performed in future studies is to show them the materials at the end of the experiment I and ask them which ones they recognized by touch; and to ask the participants at the end of experiment II how familiar they were with the materials.

Possible Gender Effects

We aimed for same number of males and females in the study in order to cancel out the gender effects. However, it is a possibility that the perception of softness might differ across genders. Some materials might be more familiar to females (chickpeas, red pepper, flour etc.) and there might be an effect of the familiarity. A post-hoc analysis might be performed in order to investigate whether having similar numbers of males and females truly cancelled out the gender effect on softness perception.

Timing

One procedural point to reconsider is the time spent on exploration of each item. Since the timing for rating the adjectives is controlled, each participant explored the given material in similar amounts of time. However, no strict control was performed on the time spent for the exploration of the material. In case a participant spent significantly more time when exploring one item than another participant, the ratings might be influenced. In a future study, “time spent exploring” might be a factor to specifically investigate.

Adaptation of the Adjective List

Another limitation is the necessity to use adjectives in the present study. The original list and the adapted list were produced very carefully with proper scientific methods; however, due to the nature of languages, it is possible that participants had some difficulties in expressing themselves. A psychological categorization task without use of words might have given data that is not subject to limitations such that the participant was not familiar with the adjective presented, or some nuances were lost when the translation between languages was performed. In our study, we sometimes had to express 3 adjectives in the original adjective list with 1 adjective, simply due to the fact that such nuances of the respective material property does not exist in Turkish. For instance, “fluffy”, “cushy”, “comfy” were included in the original list, however we had to translate them into 2 different adjectives; or “compliant” and “malleable” was translated in the best manner possible, but the translations are not often used in Turkish and might possibly create confusion for the participants. A future study in which the Turkish adjective list is created as in (Guest et al., 2011) instead of adaption might give better results.

Active Touch Procedure

Another point that can be limiting is that we preferred active touch procedure for the haptic experiment. In their study, Hollins et.al (2000) provided evidence supporting the contribution of active touch to perception of roughness. Although no difference was observed for coarse surfaces, the lack of movement in active touch resulted in an impoverishment of identifying an increase in roughness for fine surfaces in comparison to the active touch. Even when the participants were told to rate the given material on a property of their own choice, that is different than the roughness, the results were affected by the touch being active or passive for fine surfaces. They argue that such a difference may occur due to the fact that the passive touch lacks some procedural information the active touch provides; i.e. the passive touch eliminates the vibrational cues which are important for the perception of roughness. Also, in another study, the participants were able to recognize cookie-cutter forms through active touch and the performance was significantly poorer with passive touch (Heller, 1984). Some studies which included active touch did so in a highly limited manner. In the studies of material surface perception and material warmth perception (Ho & Jones, 2006), the participants were told to use only one finger and were allowed to only touch one surface of the material (Lederman &

Lederman, 1981) or only stroke with one finger (Skedung et al., 2011). It is true that these studies were more liberal in touching procedures compared to the passive touch studies and revealed more information regarding haptic perception; regardless, it is known that depending on the information that is aimed to be gathered, different hand movements are performed which are called exploratory procedures (Lederman & Klatzky, 1987). Moreover, active touch can be efficiently used by visually intact or impaired individuals in object identification and humans in general are able to very accurately perceive familiar or novel three dimensional objects due to the haptic system (Ballesteros et al., 2005). Therefore, it can be said that an active touch, not by merely stroking the material with one finger or moving one finger towards a predetermined direction on the surface of the material, but an active touch with no limitation on the exploratory procedure will give us richer information on the perception of touch since enabling hand movements enhances and manipulates the sensory input (Klatzky, Roberta L.; Pawluk, Dianne; Peer, 2013). Haptic perception is richer than passive touch as it involves cutaneous perception and kinaesthetic perception: the former of these perceptions is mediated by the mechanoreceptors and the latter is performed by the position of the fingers (Bicchi et(Bicchi et al., n.d.) al., 2005). A passive touch procedure would only provide cutaneous information while disregarding the kinaesthetic information and would consequently be less rich in terms of the information it reveals. Nevertheless, the natural haptic experience requires an integration of information coming from multiple resources and encapsulation of both cutaneous and kineasthetic inputs (Klatzky, Roberta L.; Pawluk, Dianne; Peer, 2013). As it can be seen from the literature, active touch procedure surely provides richer information than passive touch, therefore we preferred it as an exploration procedure in the present study. However; it also has its own disadvantages: since the participants were able to explore the material in a freely manner, it is a possibility that they were able to figure out what the material was. If the person understood that what they are holding is a stone, then we expect brain areas that are responsible for object perception or shape perception to become activated. It is a possibility that in this case the resulting perception was also shaped by these activations to an extent. In future studies, a replication of the present study with passive touch might be performed in order to see if active touch procedure has any disadvantages as stated above.

Conclusion

The present study, to our knowledge, is the first study aiming to explore the haptic dimensions of softness perception. It also is unique in terms of investigating the haptic information that is derived from vision only. We found that haptic and vision domains provide similar information regarding slipperiness, softness, deformability and roughness material properties, whereas a difference between these two domains is observed for granularity, stickiness and hairiness. Haptic information was more pronounced in granularity for granular materials, in stickiness for stickier materials and in hairiness for hairier materials. On the other hand, visual information resulted in higher scores of granularity, stickiness and hairiness for materials that are less granular, less sticky and less hairy. Vision exploration was found to play an enhancer role for granularity, stickiness and hairiness dimensions; making the perception more pronounced when compared to the perception via haptic exploration.

The present study contributes to future studies by suggesting the result that haptic and visual explorations provide different haptic information, which was a gap in the literature. Future studies shall address the abovementioned limitations of the study and shall focus on investigating the consistency of the difference of material properties across haptic and visual domains.

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Appendix A

Standardized Instructions for Participants for Experiment I and II in English

Experiment I

Welcome to the experiment. Please have a seat and put these ear and noseplugs. I will place a material behind this cloth screen in a glass container. Please focus on the material and not the glass container. I will give you a sign to start by nodding. You will insert your hand through the gap and explore the material in any manner you like. While you explore the item I will show you one card on which an adjective is written. Please give me a rating for this adjective regarding the extent you think it applies to the material. 1 means I do not think this adjective applies to the material at all, 7 means I think this adjective applies to the material strongly; and the numbers in between mean gradual agreement. After I write down your reply, I will show you next card and you will rate that adjective for the same material. We will complete a list of adjectives. After that, I will change the material and do the same rating task to complete the list. We have 50 different items. In case you recognize the item, please try to focus on how it feels when you touch it and do not think of your previous experience about the item. Disregard your previous ratings on different materials, please reply without making any comparison and by only focusing the given item at that time. In order to make the experiment not last longer than 2 hours, I am asking you to reply in 3 seconds for each adjective. If it takes more time I will give you a feedback of a beep noise and request your reply. We do not move on to the next adjective unless I have a rating. For some items, you might need to dry your hands with paper towel, I will help you when it is the case. If you are ready and do not have any questions, let us start.

Experiment II

Welcome to the experiment. Please have a seat and put these ear and noseplugs. I will place a material on the table in front of you in a glass container. Please focus on the material and not the glass container. I will give you a sign to start by nodding. You will only explore the material by looking. Do not hold the glass or do not touch the item. While you explore the item I will show you one card on which an adjective is written. Please give me a rating for this adjective regarding the extent you think it applies to the material. 1 means I do not think this adjective applies to the material at all, 7 means I think this adjective applies to the material strongly; and the numbers in between mean gradual agreement. After I write down your reply, I will show you next card and you will rate that adjective for the same material. We will complete a list of adjectives. After that, I will change the material and do the same rating task to complete the list. We have 50 different items. Surely you will recognize some of the items since you see it, please try to focus on how it seems when you explore it visually and do not think of your previous experience about the item. Disregard your previous ratings on different materials, please reply without making any comparison and by only focusing the given item at that time. In order to make the experiment not last longer than 2 hours, I am asking you to reply in 3 seconds for each adjective. If it takes more time I will give you a feedback of a beep noise and request your reply. We do not move on to the next adjective unless I have a rating. If you are ready and do not have any questions, let us start.

Appendix B

Standardized Instructions for Participants for Experiment I and II in Turkish

Deney I

Deneyimize hoşgeldiniz. Lütfen oturun ve burun ve kulak tıkaçlarını takın. Bu bez paravan arkasına cam bir kap içinde bir materyal yerleştireceğim. Lütfen cam kaba değil materyale odaklanın. Başımı sallayarak size başlamanız gerektiğini belirteceğim. Elinizi bu açıklıktan sokarak materyali istediğiniz biçimde inceleyeceksiniz. Materyali incelerken size üzerinde bir sıfat yazılı olan bir kart göstereceğim. Bana bu sıfatın bu materyale ne kadar uyduğunu düşünüyorsanız bir rakam söyleyeceksiniz, 1 hiç uymuyor ve 7 çok uyuyor anlamına geliyor, aradaki rakamlar da dereceli uygunluk ifade ediyor. Ben cevabınızı yazdıktan sonra bir sonraki kartı göstereceğim ve aynı materyal için bu kez o sıfata bir rakam vereceksiniz. Bu şekilde bir liste sıfatı tamamlayacağız. Sonrasında materyali değiştireceğim ve listeyi tamamlayana kadar aynı skorlama işlemini tekrarlayacağız. 50 farklı materyal var. Materyali tanımanız durumunda lütfen dokunduğunuzda nasıl hissettiğinize odaklanın ve materyalle ilgili önceki tecrübelerizi gözardı edin. Skorlamada farklı materyallere ne skor verdiğinizi düşünmeyin, karşılaştırma yapmadan sadece o anki materyale odaklanarak cevap verin. Deney 2 saatten daha uzun sürmesin diye her bir sıfata 3 saniye içinde cevap vermenizi istiyorum. Bundan daha uzun sürerse kısa bir bip sesiyle sizi uyaracağım ve cevabınızı isteyeceğim. İlgili sıfat için cevabınızı almadan bir sonraki sıfata geçmeyeceğiz. Bazı materyallerde ellerinizi kurulamanız gerekebilir, bu durumlarda kağıt havlu ile size yardımcı olacağım. Hazırsanız ve sorunuz yoksa başlayalım.

Deney II

Deneyimize hoşgeldiniz. Lütfen oturun ve burun ve kulak tıkaçlarını takın. Bu masa üzerinde önünüze cam bir kap içinde bir materyal yerleştireceğim. Lütfen cam kaba değil materyale odaklanın. Başımı sallayarak size başlamanız gerektiğini belirteceğim. Matreyali yalnızca bakarak inceleyeceksiniz. Lütfen cam kaba ya da materyale dokunmayın. Materyali incelerken size üzerinde bir sıfat yazılı olan bir kart göstereceğim. Bana bu sıfatın bu materyale ne kadar uyduğunu düşünüyorsanız bir rakam söyleyeceksiniz, 1 hiç uymuyor ve 7 çok uyuyor anlamına geliyor, aradaki rakamlar da dereceli uygunluk ifade ediyor. Ben cevabınızı yazdıktan sonra bir sonraki kartı göstereceğim ve aynı materyal için bu kez o sıfata bir rakam vereceksiniz. Bu şekilde bir liste sıfatı tamamlayacağız. Sonrasında materyali değiştireceğim ve listeyi tamamlayana kadar aynı skorlama işlemini tekrarlayacağız. 50 farklı materyal var. Gördüğünüz için birçok materyali tanıma ihtimaliniz var, lütfen bakarken nasıl göründüğüne odaklanın ve materyalle ilgili önceki tecrübelerizi gözardı edin. Skorlamada farklı materyallere ne skor verdiğinizi düşünmeyin, karşılaştırma yapmadan sadece o anki materyale odaklanarak cevap verin. Deney 2 saatten daha uzun sürmesin diye her bir sıfata 3 saniye içinde cevap vermenizi istiyorum. Bundan daha uzun sürerse kısa bir bip sesiyle sizi uyaracağım ve cevabınızı isteyeceğim. İlgili sıfat için cevabınızı almadan bir sonraki sıfata geçmeyeceğiz. Hazırsanız ve sorunuz yoksa başlayalım.

Appendix C

Materials used in the study shown in a larger scale