Indian Journal of Fibre & Textile Research
Vol. 48, September 2023, pp. 253-261
DOI: 10.56042/ijftr.v48i3.6053

Modelling and prediction of visual-haptic perception in textiles

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Received 3 February 2022; revised received and accepted 12 January 2023

The study examines the contact and non-contact assessment of textile modalities under three task conditions, namely visual, haptic, and visual-haptic combination. A comparative analysis shows that the cues perceived by flattened fabrics are insufficient to stimulate the perception of softness during the purely visual condition. At the same time, the spatial deformation caused by the action significantly stimulates the perception of softness in the purely haptic state. While in the visual-haptic dual condition, the spatial deformation causes a folding formation that stimulates the perception of softness by matching the visual and haptic cue information. The study outcomes are theoretically defined as Perceptual Conflict of Interest (PCI), which further focuses on the PCI model of fabric perceptual prediction. Accordingly, this study also discusses different concepts of sensory cue tracking and their impact on cloth modality assessment.

Keywords: Fabric hand feel, Fabric softness, Perceptual control theory, Subjective evaluation, Textile e-commerce, Visual-haptic dual conditions

1 Introduction

Textile products, in the form of garments and home textiles, create a haptic interaction when they come into contact with the human body. As a result, textile consumers are more cautious about the feel of fabrics while making their final purchasing decisions. At the same time, speculation about the haptic experience via online textile images is the most common challenge in the textile e-commerce platform[1]. This paper reports that such problems arise because of the variations in the assessment conditions that allow the tracking of visual and haptic cues during fabric modality prediction. Fabric modality prediction is a goal-directed activity. It is the highest level of cognitive function that includes the processes of sensation, perception, attention, and memory of fabric identity. The fabric modalities identified are expressed in the opposite adjectives of verbal descriptions. Usually, they have a specific meaning in communication. For example, in textile engineering, the term 'softness' is considered the opposite of 'stiffness'[2]. Softness and stiffness are considered higher-order properties because they can be measured from several detached components[3]. Softness is correlated with fabric compliance properties. Compliance relates to the viscoelastic properties of materials. Viscous properties are associated with increased force with velocity, and elastic properties link force with displacement[4]. In contrast, stiffness is associated with the flexural rigidity of the fabric[5]. At the same time, the 'stiffness' is different from 'hardness'. Hardness measures the 'resistance to various permanent changes in shape when a force is applied to a solid'[6]. Indeed, textile fabrics are reinforced composite materials that do not characterise themselves as a single solid structure. Therefore, the term 'hardness' in textiles is inappropriate to express the opposite adjective of 'softness'. However, from a haptic perception point of view, 'softness' and 'stiffness' could be distinguished by the spatial pressure distribution over the skin contact region, as sensed by the cutaneous mechanoreceptors[7].

Fabric softness is a subjective measure of the haptic modality of the fabric. Softness affects performance and functional properties, including comfort, appearance, and tailoring. The assessment of softness is therefore an essential parameter for the quality of a textile product. Softness is quantified either subjectively or objectively. Previous studies have reported that subjective and objective measurements of fabric softness are highly correlated[8]. With regard to the subjective assessment conditions, however, there are some contradictions between the studies. For example, Elder *et al.*[5,9,10] performed the subjective experiment by touch alone, while Tian *et al.*[11] and

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Zheng *et al.*[12] used the combined sight and touch method. Laughlin[13] argues that seeing may influence subjective judgments. At the same time, Tadesse *et al.*[14] suggest that in addition to pure touch evaluation, visual assessment should also be taken into account. AATCC[15] guidelines state that the evaluator may or may not look at samples during an evaluation session, although seeing may lead to biased judgments. The above contradictions indicate that the reliability of the subjective task condition in predicting fabric softness has not been addressed in depth.

Modality predictions involve many psychophysical interpretations within an explorer[16]. This is where sensory cues derive a significant amount of information while exploring an object. Sensory cues represent the properties of a stimulus that an organism perceives in a particular situation or environment in order to recognise and assess the stimulus and its properties[17]. Perception involves the organisation, interpretation, and meaning of what the initial process of sensory cues has captured. Perception integrates sensation into a level of consciousness[18]. It estimates an object's state, derived from sensory cues and previous assumptions about the object[19]. At the same time, the reliability of the sensory cues depends on 'mode of contact' or 'condition', such as visual or haptic. In the sensory organs—eye (for the visual) and skin (for the haptic)—are observed for the same modality. However, sensory stimuli react differently to the eyes and skin.

In this context, the current study discusses various conceptual phenomena related to sensory cue tracking that cause perceptual bias during visual-haptic feedback. This issue is explored by examining a frame of reference that includes three different randomly assigned tasks, viz. a haptic-alone task, a visual-alone task, and a visual-haptic combined task. Each task allows tracking of visual cues and haptic cues. The fundamental aspects of the frame of reference are based on Perceptual Control Theory, developed by William T Powers[20]. It briefly describes that, a change in disturbance varies the effect of the response (output); hence the association between stimulus (input) and response (output) is primarily controlled by environmental constraints; it leads to conflicts, mainly when one control system obtains different reference signals beyond the one system at higher levels[21]. In this regard, hypothesis for the frame of reference is : "*The obtained signals from different sensory systems affected by different sensory conditions are expected to dominate over one another. Thus, the sensory condition available to each task controls the amount of noise that corrupts the original sensory signal and therefore, expected task accuracy"*. This phenomenon is referred to in the current study as "*Perceptual Conflict of Interest (PCI)"*.

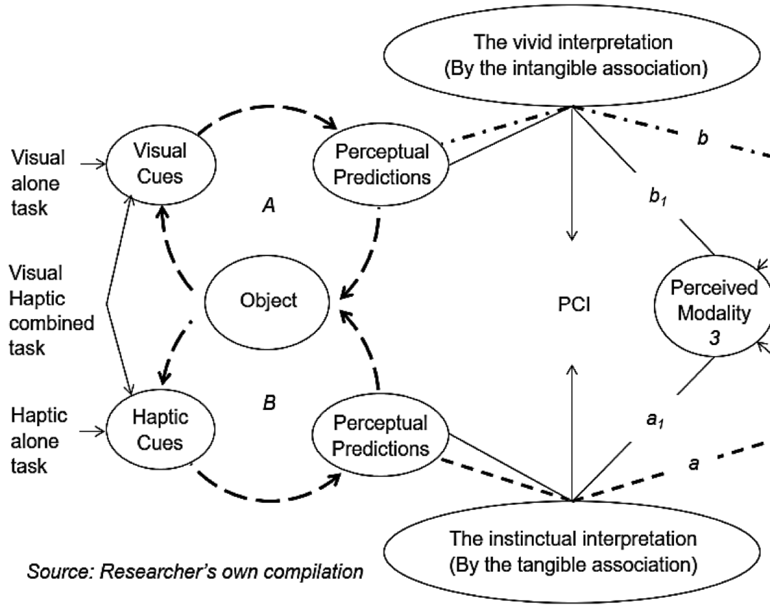
The frame of reference is analysed through experimental results and further introduces a *Perceptual Conflict of Interest model*, hereinafter referred to in this study as the *PCI model*. According to the PCI model, modality interpretations are the observed output of task conditions that drive the constancy of perceptual judgments.

2 Materials and Methods

2.1 PCI Model

To simplify the analysis, the proposed PCI model can be explained in two parts, (i) extracting and encoding the information and (ii) a comparison of acquired information in working memory. According to part one (i) photoreceptors in the eyes recognise visual cues. They convert the signals into radiant energy. While in the haptic system, skin mechanoreceptors perceive haptic cues through touch and convert the signals into mechanical energy. It shows that both sensory systems function independently.- Also, they present the sensory cues clearly, even if they are captured simultaneously by the same object. So part one (i) is similar to single-tasking. The second part (ii) deals with the transition from sensation to perception. Once sensory cues are captured, they are converted into working memory. Working memory is a short-term or temporal state for retaining task-related information during active perception[22,23]. It encodes the sensory cues and compares the subtle differences it detects to similar measures of task goals that the brain already knows. It is based on the visual and haptic conditions mentioned in the first part. The PCI model is shown in Fig. 1.

In the PCI model, the task goal defines a set of actions that are performed to arrive at a final interpretation of the perceived modalities. Task goals are typical of all three task conditions. According to the modal, the visual and haptic perceptual system structures with a circular closed-loop. The circular closed-loop system links cues corresponding to respective sensory organs (eye and skin) and perceptual predictions. It is a chain of neural processes, and the circular closed-loop system refines the identified cue information through the repeated confrontation of sensory organs with an object. During this process, the sensory impressions of the object continue to improve



Source: Researcher's own compilation

Fig. 1 — PCI model [A—Visual perceptual system. B: haptic perceptual system. 1—perceived modality from haptic-alone task, 2—perceived modality from visual-alone task, 3—perceived modality from a combined visual-haptic task. a (dashed line)—the deviated path of ‘perceived modelity-1’ in a haptic-alone task, b (dash-dot line)—the deviated path of ‘perceived modelity-2’ in a visual-alone task. a1 and b1 (solid lines)-the prediction relationship corresponds to 'perceived modelity-3' in the combined visual-haptic task. c (double-headed arrows)—the perceptual bias]

as compared to the previous state. Perceptual predictions are the difference between the top-down and the bottom-up information of the stimulus[24].

The schematic diagram illustrates that the task goal determines the nature of perceived information that acts as a controlling factor in modality prediction. The stress between vivid interpretation and instinctual interpretation leads to perceptual conflict of interest (PCI) in a combined visual-haptic task. As a result, PCI affects the accuracy of modality judgement. The PCI model shows that the transition from sensation to perception occurs under two interpretive conditions, namely (i) the vivid interpretation by the intangible association under the visual condition and (ii) the instinctual interpretation by the tangible association under the haptic condition. Vividness is the richness of perceived visual information[25-27]. This study defined the term ‘vivid interpretation’ as “comprehending the meaning of visual sensory cue rudiments cautiously and estimating them as a whole mental representation by taking advantage of prior knowledge about the visual object identity”.

From a haptic point of view, the term ‘instinct’ is used in the sense that it describes a set of unlearned haptic responses to an environmental stimulus that cannot be explained rationally[28, 29]. This study defined the term ‘instinctual interpretation’ as “*comprehending the meaning of haptic sensory cue rudiments spontaneously and allocating them as a whole mental representation without prior knowledge about the similar haptic occurrence”*. Perceptual predictions retrieve, reconstruct, and manipulate haptic working memory during the haptic-alone task, denoted as a ‘*tacit knowing’*. Tacit knowing indicates a state of mind that is observed to cohere based on numerous perceived cues, but it cannot be communicable[30, 31]. The repeated refining of cue information by a circular closed-loop system allows perceptual predictions till it saturates into a phase of instinctual interpretation. Instinctual interpretation enables the observer to convey the perceived modalities of an object in a meaningful manner. At the same time, information processing occurs in a visual-alone task in visual working memory. The saturated perceptual predictions from the visual observations carry over into the phase of vivid interpretation. It again helps the observer to convey visually perceived modalities.

Model Predictions

The model suggests a sensory-based prediction mechanism with two main synchronisations- a repeat cycle of perceptual predictions and two perceptual interpretations via perceived modality. It suggests that sensory processing leads to perceptual interpretations that are outweighed when goal-directed task conditions are controlled. A comparison between vivid and instinctual interpretations is observed.

In a visual-alone condition, the repeat cycles of perceptual predictions from visual directional cues cause vivid interpretation. In a haptic-alone condition, the repeat cycles of perceptual predictions from haptic directional cues cause instinctive interpretation. Whereas in the visual-haptic dual condition, bidirectional sensory cues synchronise two distinct repeat cycles of perceptual predictions. When the stimulus is revealed visually, the encoded optical signals arbitrarily direct the haptic tracking through a visually guided action. It grounds the continuous, dynamic nature of shifting perceptual attention within a dual condition. Bidirectional sensory cues trigger perceptual input cues to discriminate between transpiring perceptual reference and similarity cues that support domain-specific working memory retrieval. However, they enforce vivid and instinctive interpretations in an isolated manner, as sensory information processing occurs with the various closed-loop perceptual systems. Thus, perceptual predictions do not integrate perceptual interpretations into a visual-haptic dual condition; instead, they overlap each other.

Consequently, the dual sensory condition causes cognitive dissonance between vivid interpretation and instinctual interpretation to attain their common task goal of perceiving object modality. According to the proposed model, it is a state of mind called *the perceptual conflict of interest (PCI)*. PCI is defined as *"the stress associated with terminal feedback resulting from cognitive dissonance between vivid and instinctual interpretations devoted to meeting a task demand output"*. However, such a situation does not prolong due to the constraint capacity of working memory. Therefore, the task demand output might favour the most recognised sensory cues under goal-directed task conditions during manipulating modality information. Moreover, PCI acknowledges the effects of relative changes in perceptual attention as a *perceptual bias*. Perceptual bias is defined in the current study as "*the variance within the veridical sensory information and established perceptual predictions by an analogy between* uni-sensory condition *and* dual sensory condition". Hence, the PCI describes the conditional sway about mutually incompatible stimuli responses. It has an effect on perceptual experience optimisation, resulting in substantial diversity in modality judgements among perceivers.

2.2 Ethical Approval

Ethical approval for all procedures was taken from the institute. Participation in the study was voluntary. All participants involved in this study provided written informed consent before the experiments.

2.3 Subjects and Stimuli

The study involved 60 naïve participants (30 men and 30 women) between the age group of 18 and 40 years. None of the subjects had any expert knowledge or special skills with haptic and visual evaluation. All the participants were unaware of the purpose of the study. Fabric specimens (15 × 15 in) with the same construction parameters were used in all experiments.

2.4 Methodology

The present study used the terms 'soft and stiff' as the bipolar modality to assess the subjects' responses. The study used English verbal descriptions, which were manipulated by the researchers to assess the effect on a subject's psychophysical feedback. This strategy allows subjects to perceive sensory cues and the associated geometric shapes [32-34]. To describe the stimulus quantitatively, the bipolar modality (soft and stiff) is grouped into two sets of verbal descriptions. Verbal descriptions indicate sensory cues; they are opposite adjectives as shown in Table 1. The most desirable choice of sensory cues is determined by task conditions. For example, in a purely haptic condition, subjects' psychophysical feedback relies on haptic cues. Similarly, in the visual-alone condition, psychophysical feedback depends on visual cues. While in a visual-haptic dual condition, the psychophysical feedback of subjects relies on both haptic and visual cues.

The psychophysical trial was conducted against fabric stimuli to detect softness modality under three task conditions-viz.visual, haptic, and visual-haptic dual condition. A non-comparative evaluation technique was used to examine the fabric and visual/haptic interaction in all experiments. This experimental technique included both a contact and a non-contact method. The contact method means repeated squeezing of the fabric stimulus

Table 1 — Verbal description index

Haptic		Visual	
Stiffness	Softness	Stiffness	Softness
Thick	Thin	Duller	Brighter
Dense	Loose	Matt	Glossy
Heavy	Lightweight	Dimmer	Shimmer
Hard	Spongy	See-through	Opaque
Rigid	Flexible	-	-

between the fingers and palm area, while the non-contact method indicates only visual observation. Discrimination thresholds were measured in the Semantic Differential (SD) method with a rate of 1-5. In this method, the perceptual scale represents two adjectives as an opposite pair, which refers to the bipolar modality[35].

The experimental method of this study defines the following: (i) sensory cues act as a means of communication between stimuli and the observer, (ii) a task is a measurable activity performed by individuals to meet experimental requirements, (iii) the condition is the state of the participants who are introduced to an uni-sensory environment in which they only have to perform one task at a time, and (iv) a dual condition is the state of participants being introduced simultaneously to a multi-sensory environment in which the person is only required to perform one task at a time.

2.5 Experimental Setup

In the first experiment, a black-coloured box with two hand-holes was used to hide the fabric from the participant's sight. In the second experiment, the fabric was mounted on a hollow square frame and positioned inside a front-opening grey-coloured box. In the third trial, another front-opening grey-coloured box was used. The box with the fabric specimen was placed on a table. Furthermore, an LCD monitor connected to the CPU was used for the feedback record. Cool daylight (Pureline SP680P: colour temperature: 6500 K, luminaire light beam spread at 110°) was uniformly used throughout the time of experiment.

2.6 Protocols

The assessment protocols were accompanied as per the AATCC[15] guidelines. A demonstration was held. Each sequence of experiments began with a haptic-alone condition, followed by a visual-alone condition, and a visual-haptic dual condition. Participants were only allowed to touch the sample on the first experiment. Conversely, in the second attempt, participants were not allowed to touch; instead, they observed the stimulus visually. Whereas in the third trial, the participants could freely touch and see the given sample. Only one stimulus was provided at a time in random order. Each sample was only replaced after confirming the completion of the task. Participants made their choices based on the verbal descriptions displayed on the LCD monitor. After each completed task, the each participant was asked to rate the identified perceptual value on the given scale by pressing the appropriate keys on the keyboard. Participants were allowed to take their own time for exploration. An informal interview was also conducted after the experiments.

2.7 Statistical Analysis

Multiple regression was performed to identify the relationship between perceptual responses for each trial. In addition, the correlation statistics were used to calculate the significant relationship between verbal descriptions representing the haptic and visual cues. For all statistical tests, a probability level of $p<0.05$ was considered statistically significant. The significantly affected verbal descriptor is analysed by the repeated N (number) tally. In addition, data visualisation methods such as table charts and scatterplots were used to analyse the influences of the cues. All data derived from participants' feedback was calculated using Minitab version 19.

3 Results and Discussion

3.1 Haptic-alone Condition

The results of the haptic-alone experiment are given in Table 2. The results show that haptic cues 'thin' (-0.551, $p=0.001<0.05$) and 'light' (-0.450, $p=0.036<0.05$) are statistically significant. They act as predictors of 'soft/stiff' modalities. Also, haptic cues contribute ~23.38% variation in the response feedbacks at a 95% confidence level.

The results show that the accuracy of haptic perception increases with increasing observed haptic cues. In the purely haptic condition, bipolar sensory cues

Table 2 — Regression and tally analysis of haptic cues

Haptic cues	Coefficient	SE coefficient	T value	P value	Count	Per cent
Thick	0.800	0.456	1.75	0.085	1	1.67
Dense	0.800	0.456	1.75	0.085	1	1.67
Thin	-0.551	0.159	-3.47	0.001	37	61.67
Light weight	-0.450	0.209	-2.15	0.036	8	13.33
Spongy	-0.200	0.456	-0.44	0.663	1	1.67
Flexible	-0.200	0.197	-1.01	0.316	10	16.67
Loose	-0.200	0.338	-0.59	0.557	2	3.33
R^2 value	23.38%	-	-	N=	60	-

Table 3 — Regression and tally analysis of visual cues

Visual cues	Coefficient	SE coefficient	T value	P value	Count	Per cent
Duller	1.028	0.250	4.11	0.001	6	10.00
Matt	0.653	0.221	2.95	0.005	8	13.33
Dimmer	0.428	0.271	1.58	0.120	5	8.33
See-through	1.028	0.188	5.46	0.001	12	20.00
Brighter	-0.790	0.195	-4.06	0.001	11	18.33
Glossy	-0.972	0.221	-4.39	0.001	8	13.33
Shimmer	-0.401	0.234	-1.71	0.093	7	11.67
Opaque	-0.972	0.341	-2.85	0.006	3	5.00
R^2 value	64.92%			N=	60	

'thick/thin' and 'heavy/light' are recognised by hand-finger movements. It is a bottom-up signalling process. During the finger-cloth interaction, the encoded signals enhance the haptic working memory. The retraced information from the haptic working memory reverts to finger pads for further action which results in haptic cues reconfirmation. It is a top-down signalling process. At the same time, the simultaneous bottom-up and top-down process leads to some perceptual predictions. The repeat cycle of perceptual predictions causes discrimination between 'thick/thin' and 'heavy/light' bipolar sensory cues. It is an *instinctual interpretation* by the *tangible association* under *purely haptic conditions.* Tally (Table 2) analysis also shows that the majority of subjects rely on the cue 'thin' (61.67%) followed by 'flexible' (16.67%) to identify 'soft' as the perceived modality of the fabric swatch examined.

3.2 Visual-alone Condition

According to the results of the visual-only experiment, all eight visual cues are involved in determining the soft/stiff modalities (Table 3). Approximately 64.92% of the variation in response feedback is observed at the 95% confidence level. The results show that except for the dimmer and shimmer cues, remaining are statistically significant (p=<0.05).

Also, there is a negative linear relationship between visual cues and feedback. It points out that as reliance on visual cues increases, the accuracy of feedback decreases. Therefore, visual cues do not accurately predict the modalities of the given swatch in a visual state. In other words, the participants could not judge the given fabric swatch to be either 'soft' or 'stiff' through visual observations. At the same time, the tally (Table 3) analysis indicates that the visual cue 'see-through' (20.00%) is the most significantly influenced visual cue by the subjects. Thus, they become better determinants among the visual cues for detecting softness. The term 'see-through' indicates how an object transmits *visible light*.

Experimental performance is based on fabric stimuli, where the spacing between yarns controls the transmission of visible light. The fabric specimen used in the experiments is *translucent*. The translucent fabric diffuses visible light as it passed through. Thus, the 'thin areas' of the material appear to *glow,* while 'thicker areas' do not. It causes shadows from surface relief and the shape is visually perceived as *softer*[36]. It occurs because, when the observer visually assesses the object shape, the visual system examines the shape-related regularities of the retinal image[37]. Therefore, the translucency perceived by the observer strongly influences the accuracy of geometric acuity compared to opaque material[37,38].

In fact, regression results indicate that the statistically significant visual cues are bipolar in nature. This is strong empirical evidence that the repeat cycle of perceptual predictions does not discriminate between the bipolar visual sensory cues in the visual-alone state. Ideally, the most recognised visual cues enhance the visual working memory during the visual-alone task. Although this evidence suggests that most participants could rely on the stored information from long-term visual memory for visual assessment of objects. It occurs due to the strong relationship between visual working memory and long-term visual memory[39].The relationship between working memory and long-term memory causes the unexpected retrieval of incidental episodic memories in a visual context[27]. It is deeply rooted in vivid visual mental imagery, which provides evidence of *the vivid interpretation through intangible association* under *visual conditions.* Therefore, the present study demonstrates that visual observation alone confounds the recognition of visual cues that lead to a reliable prediction for a critical assessment of the soft/stiff modalities of the stimuli. In the informal interview after the experiment, most of the participants indicated that the visual-alone condition is the most challenging among other conditions. It is also observed that the visual task takes more time from the participants.

Table 4 — Regression analysis of visual & haptic cues

Parameter	Coefficient	SE coefficient	T value	P value
Feedback by visual				
Duller	-0.083	0.218	-0.38	0.706
Matt	-0.052	0.315	-0.16	0.871
Dimmer	0.394	0.295	1.34	0.188
See-through	-0.182	0.394	-0.46	0.647
Brighter	0.185	0.280	0.66	0.511
Glossy	-0.486	0.464	-1.05	0.300
Shimmer	0.188	0.342	0.55	0.585
Opaque	0.036	0.364	0.10	0.922
R^2 value	14.15%			
Feedback by haptics				
Thick	-0.372	0.516	-0.72	0.475
Dense	-0.372	0.516	-0.72	0.475
Thin	0.701	0.252	2.78	0.008
Lightweight	0.225	0.328	0.69	0.495
Spongy	-0.049	0.378	-0.13	0.897
Flexible	0.146	0.211	0.69	0.493
Loose	-0.279	0.305	-0.92	0.363
R^2 value	21.80%			

3.3 Visual-haptic Dual Condition

A regression analysis of visual and haptic cues in the dual sensory condition is given in Table 4. According to regression analysis, there is approximately a 21.80% variation in touch feedback under haptic conditions. At the same time, the variation in feedback by look is approximately 14.15% in the visual condition. The haptic condition coefficient results show that the haptic cue thin (0.701) is statistically significant at the 95% confidence level ($p=0.008<0.05$). In fact, none of the visual cues are statistically significant when it comes to visual condition.

Tally (Table 4) analysis shows that 45% of the participants rely on the haptic cue ‘flexible’ to predict the modality in a visual-haptic dual condition. In contrast, it is not statistically significant in the regression analysis. At the same time, 'thin' (20.00%) is the second most trusted haptic cue. Also, it is statistically significant in the regression analysis. A variation in responses to both visual and haptic feedback is also reported. For example, in the third experiment, variation in haptic feedback decreases, while in visual feedback it is increased. Similarly, the percentage of participants' responses to the sensory cue ‘thin’ also decreases. Whereas the response to the sensory cue ‘flexible’ increases significantly in the third experiment as compared to the first trail.

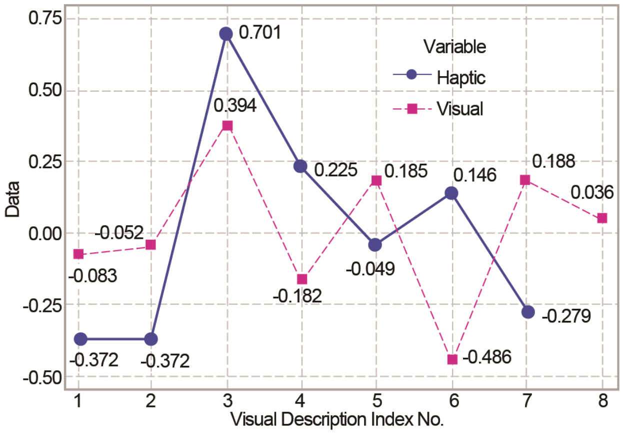


Fig. 2 — Comparison of visual & haptic coefficient

Figure 2 illustrates a combination plot of the visual- haptic coefficient. It is observed that haptic cues are more dominant than visual cues, although visual cues almost follow the haptic pathway. The analysis points out that visual cues can significantly influence haptic cues during haptic exploration in a visual-haptic dual condition.

In the plotted diagram, the straight line indicates the corresponding values of the haptic coefficient. The dashed line connects the visual coefficient. The comparison shows that the visual cues almost follow the haptic path. In the first task (haptic-alone), the regression result shows that the cue ‘thin’ influences participants' responses, followed by the other cue, ‘lightweight’. At the same time, in the third task (visual-haptic dual condition), the haptic cue ‘lightweight’ isreported as statistically insignificant. However, the tally and pareto chart analysis indicates that participants detected the cue ‘flexible’ differently. For example, in the first task, participants rely entirely on hand-finger movements to detect the cue ‘flexible’. It occurs because the stimulus is blocked from the participants’ sight in the first task condition. In fact, for the third task, there is no constraint on seeing the stimulus when touched. As a result, participants rapidly recognise the cue ‘flexible’ visually in addition to hand-finger movements. Hence, the cue ‘flexible’ represents an action (of bending) in the haptic-alone condition. Although, it seems to be more of a visual orientation change (by spatial deformation image) in the visual-haptic dual condition. It reveals that the information provided by the cue ‘flexible’ relied upon the *task condition*. It is evident that task conditions play a major role in controlling how participants recognise sensory cues. When participants are visually relieved, their perceptual attention generally falls into the visual focus of the fabric folds and the effect of flexibility during the softness assessment.

In a visual-haptic dual condition, rigid/flexible identification behaves differently. In the haptic frame of reference, the identification of 'rigid/flexible' sensory cues significantly depend on active touch. In addition, it is associated with the viscoelastic properties of the materials that produce an increased displacement force[4]. In general, active touch generates two types of forces: one, a force opposing the direction of hand-finger movement; and two, a force applied in the same direction as the hand-finger motion[40]. However, active touch causes a pressure distribution between the stimulated skin surface and the fabric material, producing both 'cutaneous' and 'kinaesthetic' sensory signals. Thus, softness detection is a motor interference task. In this way, the finger-fabric interaction instinctually detects changes in fabric bending force. When the observer is engaged in haptic exploration, hand-finger movements capture spatial information about the stimuli. It is achieved through a given task goal that mentally practices hand-finger movements in a typical format of exploratory patterns. These executed movements are represented as 'bending actions' in softness detection. This would mean that the repeat cycle of perceptual predictions recognise and discriminate against the amount of biomechanical force related to the haptic cue 'flexible' (through action) in the first and third experiments. The flexibility action tracks the haptic-spatial information (thick/thin in this case), that is instinctively interpreted as 'softness'.

In the visual frame of reference, the hand-finger movements cause the fabric surface to curve by bending. During the task, the observer's eye tracks the positional variation of the hand and fingers (bending motion) and focuses on the curvature shape of the fabric (spatial deformation). The 'rigid/flexible' sensory cues are optically active in response to the spatial deformation of the stimuli. The spatial deformation of the fabric results from an applied biomechanical force that determines the degree of curvature. In addition, the causal relationship between the formation of curvature and applied biomechanical force is tracked at the curvature extent (fabric folds). Accordingly, visual cues increase through the following dynamic scenes: (i) recovery of the curvature to its original shape when hand-finger force on the fabric is removed; and (ii) the amount of curvature remains constant. The dynamic scene sequences are perceived visually as multi-frame motion information[41]. The repetition cycle of perceptual predictions is confirmed in each dynamic scene during hand-finger movements. In this way, the sensory cue 'flexible' is recognised and visually distinguished in the third experiment. Identifying the visual cue (curvature shape) is an image modality recognition task. This process links both visual working memory and visual long-term memory to an experience of vividness[39]. Thus, it triggers the remembered visual setting in long-term visual memory and causes a *vivid interpretation* of the softness modality. It suggests that sensory cue 'flexible' enhances visual working memory more than haptic working memory in the visual-haptic dual condition.

It is further assumed that the visual working memory quickly incorporates the optical signal transformations into the associative processes of the visual long-term memory when the viewer is dependent on a visual scene. Thus, the visual working memory continually recaptures the visual cue information. In this process, incidental episodic memories of earlier haptic experiences translate into implicit visual information.

4 Conclusion

This study finds that the perceptual process of discriminating soft/stiff modalities is conditionally oriented, with cue information identified by (i) action associated with spatial deformation in the haptic condition, and (ii) observed visual scenes of spatial deformation in the visual condition. It is also found that there isa covert attentional shift between action and observed visual scenes in the visual-haptic dual condition. Therefore, the judgement among soft and stiff modalities is probably biased towards visual information. In this context, it is hypothesised that the simultaneous cue information evoked by the visual-haptic dual condition is not integrated into a single interpretation. But they increase the probability of multiple interpretations across the modality predictions by overlapping each other. The PCI model supports the above notion that the visual-haptic dual condition leads to a stressful situation between task-specific cues and task-goal-related representations at a metacognitive level. Consequently, concerning softness modalities, it is suggested that haptic conditions alone enhance a greater sense of realisation, whereas the presence of visual cues leads to an approximation. This assumption indicates that vision reinforces the aesthetic relationship between textile products and the viewer while touch forms a complex impression of comfort-based interactive applications for textile users.

This study focused on the effect of task conditions on sensory cue tracking in relation to the final measure of subjective fabric softness. All interpretations depend on existing knowledge about the human haptic system and its relevant domain. The degree of accuracy of fabric modalities is subjective, and the results are predicted based on the most agreed-upon feedback. Hence, the mathematical basis for determining the functions of the PCI model must also be examined in future studies.

The present study has profound implications in the textile e-commerce domain. It helps to predict how much the customer will admit to the hand feel before launching a new end product into the online textile market. In addition, the study provides a basis for future directions to narrow the gap between contact and non-contact judgement of textile modality. It would benefit further research by including the auditory stimuli that may interfere with haptic perception and haptic-specified verbal descriptions. Thus, it enhances the haptic involvement of interaction-design and product quality assurance in the textile e-commerce domain.

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