VPS Tactile Display: Tactile Information Transfer of Vibration, Pressure, and Shear

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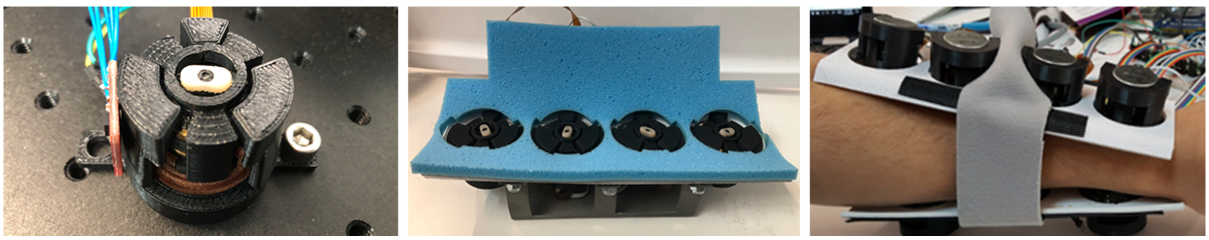

Fig. 1. From left to right: VPS taxel, VPS display consisting of 4 VPS taxels, and VPS display mounted on a user's forearm

One of the challenges in the field of haptics is to provide meaningful and realistic sensations to users. While most real world tactile sensations are composed of multiple dimensions, most commercial product only include vibration as it is the most cost effective solution. To improve on this, we introduce VPS (Vibration, Pressure, Shear) display, a multi-dimensional tactile array that increases information transfer by combining Vibration, Pressure, and Shear similar to how RGB LED combines red, blue, and green to create new colors. We characterize the device performance and dynamics for each tactile dimension in terms of its force and displacement profiles, and evaluate information transfer of the VPS display through a stimulus identification task. Our results indicate that the information transfer through a single taxel increases from 0.56 bits to 2.15 bits when pressure and shear are added to vibrations with a slight decrease in identification accuracy. We also explored the pleasantness and continuity of VPS and the study results reveal that tactile strokes in shear mode alone are rated highest on perceived pleasantness and continuity.

CCS Concepts: • **Human-centered computing → Haptic devices**; *User studies*; • **Hardware → Haptic devices**.

Additional Key Words and Phrases: VPS Tactile Display; Multi-dimensional Haptics; Pleasant Touch; Haptics

ACM Reference Format:
Lawrence H. Kim, Pablo Castillo, Sean Follmer, and Ali Israr. 2019. VPS Tactile Display: Tactile Information Transfer of Vibration, Pressure, and Shear. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 3, 2, Article 51 (June 2019), 17 pages.
https://doi.org/10.1145/3328922

1 INTRODUCTION

Human skin is equipped with various sensors that span from mechanoreceptors to detect mechanical skin deformation to thermoreceptors that respond to changes in skin temperature. Thus, we experience multi-dimensional tactile sensations where many of these receptors are triggered by an external stimuli.

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2019. 2474-9567/2019/6-ART51 $15.00
https://doi.org/10.1145/3328922

However, current consumer-use haptic interfaces lack capabilities to stimulate different types of mechanoreceptors. Instead, they primarily use vibrations to convey relatively simple information such as a notification of a new message or an event reminder. While vibration offers strong tactile sensations at a low cost and within a small form factor, its limited information bandwidth [40] and inability to activate multiple types of mechanoreceptors severely restricts the number of unique messages or notifications that can be communicated and the quality of the sensation.

To expand the information bandwidth and the realism of the sensation, researchers have explored other tactile dimensions to stimulate different types of mechanoreceptors in the human skin through shape change [19], skin stretch [34, 38], squeezing [29, 31], and brushing [39]. By stimulating a wider range of mechanoreceptors, there is a potential to communicate abstract yet meaningful information in a discreet and realistic manner within a limited area of skin. For instance, Dunkelberger and colleagues investigated user's learning and processing capacity of broadband tactile information similar to that derived from speech [9].

Here we present VPS (Vibration, Pressure, Shear) display (Fig. 1), an array of multi-dimensional tactile pixel (taxel) that can mechanically stimulate the user's skin through vibration, pressure, and shear (VPS). The concept of VPS display is similar to that of an RGB LED. Each taxel has three degrees of freedoms and can combine them to produce new effects. These taxels are formed into an array to further increase the degrees of freedom and therefore the information transfer capacity. This layout also enables us to produce stroke-like gesture that has been found to be one of the most pleasant gestures [26, 47].

After presenting the design of VPS display, we provide technical evaluations of its performance with regards to each of its tactile dimensions in terms of force/torque and displacement/rotational speed. To better understand how users perceive VPS, we conducted a user evaluation consisting of four studies. The first study sought to investigate the perceptibility and information transfer capacity of VPS display when vibration, pressure, and shear are presented with a single taxel. The remaining three studies focused on exploring human perception of VPS stimuli in terms of pleasantness and continuity when presented with a single VPS taxel or an array. In the future, we will use the study results to inform the design of devices such as a wearable watch capable of communicating discreet multi-dimensional tactile messages or a wearable sleeve that can provide calming tactile strokes on the arm during social interactions.

2 RELATED WORK

2.1 Vibrotactile Stimulation

Vibrotactile (VT) stimuli activate rapidly adapting mechanoreceptors, the Pacinican and Meissner's corpuscles depending on the frequency of the vibration [10, 43]. A common VT transducer is an eccentric rotating mass (ERM) motor that shakes the entire motor assembly given an applied voltage. The frequency and amplitude of these transducers are coupled together and vary with the speed of the motor [20]. While most commercial haptic devices are limited to a fixed frequency (e.g. as in Linear Resonant Actuator (LRA)), haptic researchers have explored other means such as voice coil transducers to expand the usable frequency and amplitude range of vibrotactile stimuli and thus the information transfer bandwidth [1]. Thin films of piezoelectric stacks are also used to render VT sensations on handheld devices that create the perception of button clicks [32, 33] and textures [45].

To further expand the information bandwidth of VT displays, haptic researchers have designed tactons with varying earcon-like parameters such as frequency and duration [4], increased the number of vibrotactile transducers, and varied their spatial layout. Rather than simply activating each transducer separately, researchers have used these discrete vibrotactile grids to produce continuous 2D motion on the skin [17, 24, 30]. These illusory movements have been used in a variety of embodiments to convey multi-dimensional haptic effects to enrich children stories [49], social interactions [14, 18], and speech communication with the skin [35, 48].

2.2 Non-Vibrational Haptic Stimulation

Researchers have also investigated ways to stimulate different mechanoreceptors such as slow-adapting Merkel's disks and Ruffini endings. These mechanoreceptors respond to skin strain changes in pressure or shear [10], and henceforth researchers have used various ways to provide pressure such as through voice coil [8], pneumatics [5], belt tightening [29], shape change [19], airflow [25, 37], drone [46], etc. To render skin stretch or shear sensation, haptic devices have been developed with mechanisms like belt/wire tightening [29] and tactor displacement [2, 11, 15, 34]. While these devices can provide more realistic and "organic" sensations compared to VT devices, they lack the throughput or information bandwidth that VT devices offer due to the slow response characteristics of both the transducers and corresponding mechanoreceptors. Thus, we propose to address this by combining both VT and non-vibrational haptic dimensions (pressure and shear) in a single package to expand the types of mechanoreceptors triggered and the information bandwidth.

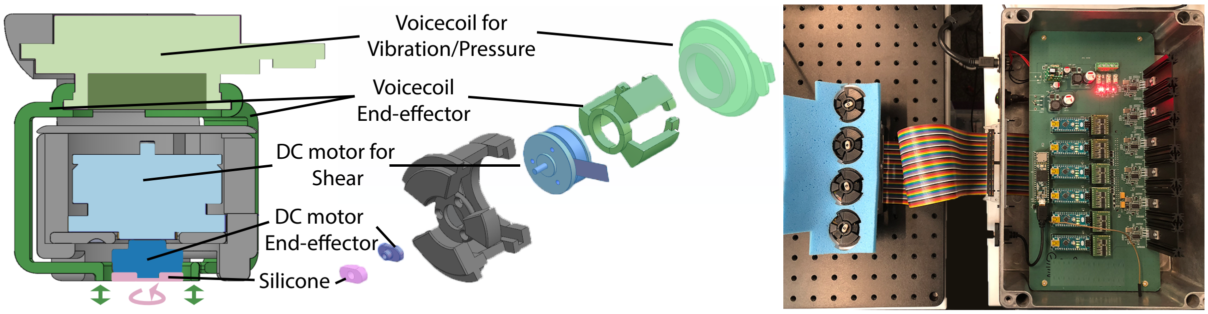
2.3 Multi-dimensional Tactile Stimulation

Integrating different tactile stimulations can enlarge the range of haptic outputs, thus enhancing the haptic experience rendered with an artificial display. A number of researchers have developed different mechanisms to stimulate different mechanoreceptors with a single device at various locations. Minamizawa et al. used a moving band around the wrist to provide both shear and pressure [29], while Caldwell et al. developed a pneumatic array to apply shear and tactile cues at the fingertip [5]. Kim et al. developed a six-bar mechanism that could provide shear, pressure and vibration cues [22] while Kim and Follmer used swarm robots to provide shear and normal forces [23]. However, neither can produce multi-dimensional tactile cues simultaneously. To enable simultaneous multisensory feedback, Dunkelberger et al. combined three bands around the arm with three actuators that squeeze, skin-stretch, and vibrate albeit not at the exact same location [9]. Haptic Revolver combined touch, shear, texture, and shape rendering to improve VR experience but no study was conducted to measure the tactile information transfer [44].

We hypothesize that users will be able to process a larger amount of information through multi-dimensional tactile cues, compared to when only vibrations are presented, as information could be transferred through more mechanoreceptors. However, these cues could interfere with each other due to collocation of the stimuli and masking between the receptors. To test this hypothesis, we developed VPS display, a multi-dimensional haptic device that could stimulate various mechanoreceptors by generating vibration, pressure, and shear sensations at the same location, and conducted a set of user studies to evaluate the added benefits of these multiple tactile dimensions.

2.4 Pleasant Touch

As the applications for haptic devices expand, it is important to generate haptic sensations that are not only perceptible but also pleasant. Prior literature show that activation of C-Tactile (CT) afferents have strong correlation with pleasant touch [27] and that they respond most vigorously to gentle and soft brush stroking, at brushing velocities of 1-10 cm/s [26]. In addition, Yohanan et al. showed that hug, stroke, and rub gestures have the highest pleasantness ratings through user studies [47]. As such, many haptic researchers have designed arrays of taxels to produce pleasant stroking sensations [8, 13, 14, 16, 17]. For instance, Huisman et al. [14] used an array of vibrotactile actuators (fixed frequencies) to modulate stroking sensations using the Tactile Brush algorithm [17], which utilizes psychophysics of sensory illusions in touch, or Apparent Tactile Motion, to create smooth, continuous and illusory motion on the skin. More recently, Culbertson et al. rendered pleasurable strokes using an array of indenters on the forearm [8] and Israr & Abnousi studied the relationship between pleasantness and vibration frequencies in an array form [16]. We also believe the ability to render pleasant haptic stimuli is



(a) Cross sectional and exploded views of VPS taxel

(b) VPS display (left) with the driver circuit

Fig. 2. Left figure shows the internal structure of the VPS Taxel while the right demonstrates the VPS display with four taxels in a row.

important. Thus in addition to finding the information transfer, we also investigated the pleasantness of each tactile dimension and combinations of them.

3 VPS DISPLAY

The VPS display aims to convey richer haptic feedback by combining vibration, pressure, and shear. Due to the lack of actuators that can provide all of them simultaneously, we combined two actuators to create each VPS taxel: a voice coil to provide vibration and pressure (Tectonic Elements Ltd, TEAX19C01-8) and a DC motor for rotational shear (Maxon Precision Motors, Inc., EC 20 flat). To further increase the expressivity, we combined four VPS Taxels in a row to create VPS display as shown on the left side of Fig. 2b. It is designed to be mounted on the user's forearm as the arm is one of the more socially appropriate areas to touch [41].

3.1 Hardware

Each VPS taxel consists of a voice coil placed on top of a DC motor as shown in Fig. 2a. This placement prevents any wire entanglement during the rotation of the DC motor. To best stimulate a single perceived point, we designed the voice coil end-effector (an annulus of 14 mm outer and 12 mm inner diameter) around the DC motor end-effector (a 5 mm slider rotating along the shaft axis) and the voice coil transmission (dark green regions in Figure 2) that translates the voice coil motion to the end-effector. Around these end-effectors, there is a support structure that serves both as the reference level to the neutral position of voice coil and as a way to limit the forces applied directly to the actuator end-effectors. On the end of the DC motor end-effector, a silicone material is attached to maximize the shear force and provide softer feel to the users. The dimensions of VPS Taxel are 42 mm in diameter and 35 mm in height.

We placed four VPS taxels in a row with an inter-taxel spacing of 4.9 cm. VPS display along with its driver circuits are shown in Fig. 2b. To control the VPS taxels, a master microcontroller (Teensy 3.6) communicates with Arduino Nano microcontrollers which then drive one VPS Taxel each. The voice coil is controlled with a DAC (MCP4725), two Op-Amps (OPA4196ID, LM675), and a digital potentiometer (MAX5400). The brushless DC motor is driven by a digital EC speed controller (Maxon Precision Motors, Inc., DEC module 24/2). Max Cycling 74 software is used as the interface to control and coordinate haptic outputs of the VPS display.

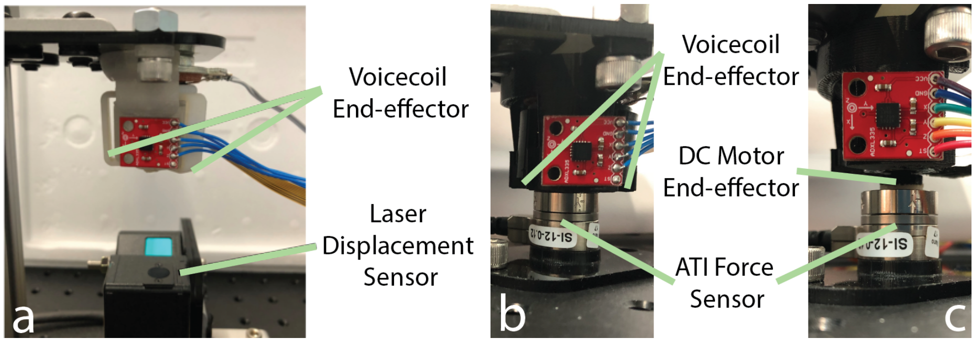


Fig. 3. Measurement apparatus for (a) displacement, (b) force and (c) torque, using a laser displacement sensor and a 6-axis force sensor

3.2 Technical Evaluation

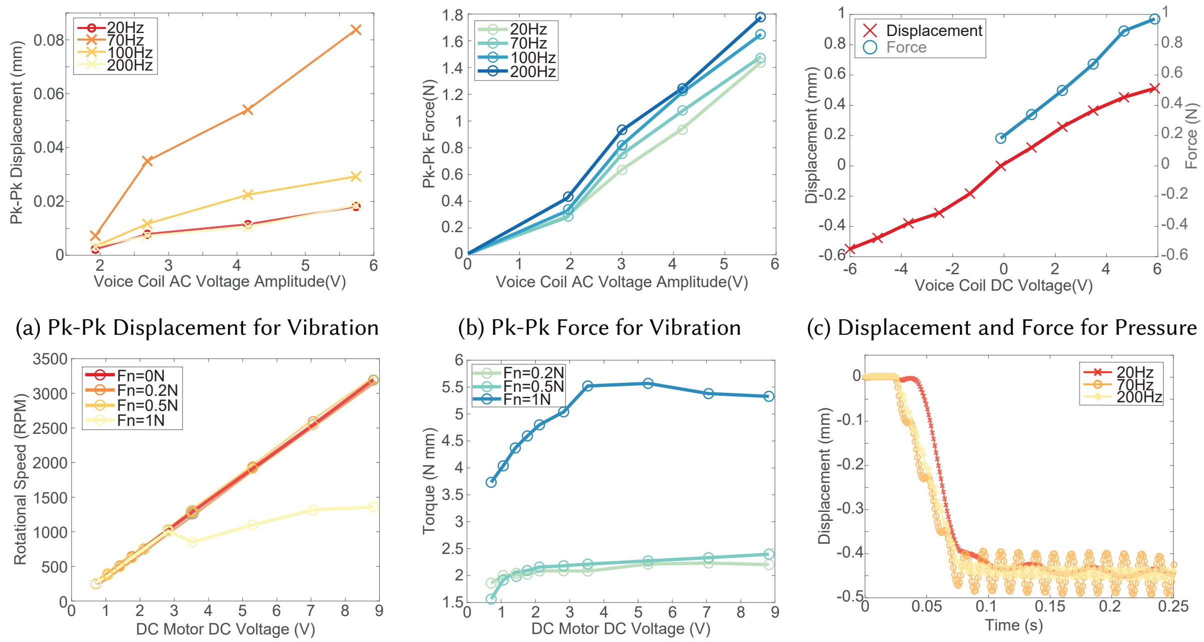
To characterize the performance of VPS display, we evaluated each tactile dimension in terms of its displacement/rotational speed, and force/torque using the apparatus shown in Fig. 3. A laser displacement sensor (Keyence Corp., LK-H052) measured the voice coil end effector's displacement, while a 6-axis force sensor (ATI Industrial Automation, Inc., Nano17) at the contact point was used to measure the resulting forces and torques. To ensure contact with the end-effectors, we preloaded them at approximately 0.2N. Finally, the built-in hall effect sensors (Maxon Precision Motors, Inc.) were used to measure the rotational speed of the DC motor.

3.2.1 Vibration. For vibration, we measured the displacement and force for different frequencies and applied voltages as shown in Fig. 4a-4b. As expected, the pk-pk displacement and pk-pk force increase with an increase in AC voltage amplitude. Different slopes in displacement profiles indicate variable gain as a function of frequency, with the highest gain (resonance peak) at roughly 70 Hz. The force profiles do not vary with frequencies, and are directly related to the applied voltage indicating a consistent resistive load of the voice coil in the operating range. The average rise time from 10% of its displacement amplitude to 90% is 41 ms.

3.2.2 Pressure. We measured the displacement and force of pressure given different applied voltage as shown in Fig. 4c. Again, as expected, both the indented displacement and the force are proportional to the applied voltage with some tapering at the ends. The average rise time from 10% of its displacement to 90% is 43 ms.

3.2.3 Shear. For shear, we measured the rotational speed under different loads (0-1N), and the torque applied by the motor at different applied voltages and loads. The measurement profiles are shown in Fig. 4d-4e. Rotational speed under no load (0 N) condition is linear with the applied voltage. When the motor was tested under loaded conditions, the motor responded linearly with small loadings (up to 0.5N). With 1 N load, the voltage increased the rotational speed up till the motor reached close to its stall torque, and rather than the end-effector sliding on the test surface it stuck-and-slipped. This is shown by saturation of force and rotational speed at roughly 3 Volts. Therefore, it was determined that the loading of 0.5 N was sufficient for the motor to slide on the contact surface. The average rise time from 10% of its rotational speed to 90% is 175 ms.

3.2.4 Vibration & Pressure. We also measured the dynamic displacement response when vibrations of different frequencies (20, 70, 200 Hz) but same AC voltage (4 V) are combined with pressure as shown in Fig. 4f. As expected from Fig. 4a, 70 Hz vibration has the highest amplitude while 20 and 200 Hz have similar lower amplitude. As the



(a) Pk-Pk Displacement for Vibration

(b) Pk-Pk Force for Vibration

(c) Displacement and Force for Pressure

(d) Rotational Speed for Shear

(e) Torque for Shear

(f) Dynamic Displacement Response for Vibration with Pressure

Fig. 4. (a) and (b) show the measurements for displacement and force respectively for vibrations under different frequencies and applied voltages. (c) plots displacement and force measurements for pressure under different applied voltages. (d) and (e) shows the measurements for rotational speed and torque respectively for shear under different applied voltages.(f) shows the dynamic displacement response when different frequency vibrations are combined with pressure.

voice coil has a finite range for its displacement, when combining vibration with displacement/pressure close to its limits, the amplitude of the vibration will decrease as it can't actuate further past its limits.

3.3 Pattern and Parameter Design

Before the main experiment, we designed the patterns and parameters of the tactile cues by piloting on three participants.

3.3.1 Vibration. For vibration, there are two parameters: frequency and amplitude. From preliminary testing with voice coils, we could easily distinguish three levels of frequencies in 20-200 Hz range, and thus selected three test frequencies (20, 70, and 200 Hz) for the main experiment. In order to tune the amplitude of each frequency such that the perceived amplitudes were approximately equal, we performed the method of adjustment: First, participants tuned the amplitude for 20 Hz vibration such that it is clearly perceptible resulting in a 20Hz vibration with pk-pk displacement of 0.011 mm. Then, participants adjusted the amplitudes of 70 and 200Hz vibrations until they had the same perceived intensity resulting in pk-pk displacement of 0.024 mm and 0.003 mm for 70 Hz and 200 Hz respectively.

3.3.2 Pressure. Different pressure profiles were designed including abrupt step profiles, and gradual ramp outputs. As the pressure driven by a voice coil is relatively weak compared to vibration, the detectability of the stimulus was the most important criterion. In a pilot study, participants rated the detectability of the pressure profiles. Results suggested that a step output profile was the most detectable and thus was used in the main study. We then had the participants tune the displacement of pressure to match the perceived intensity with that of the vibrations resulting in displacement of 0.453 mm.

3.3.3 Shear. For shear, there were three distinct modes: slip, stick-slip, or stall. Slip is when the end-effector is mostly spinning on top of the skin whereas stick-slip is when the actuator periodically stalls briefly then spins rapidly. Stall is when the actuator completely stops and is unable to provide enough torque to overcome the friction and loading. Due to the relatively low torque of the motor, we tested how well participants detected the direction of the shear (CW/CCW) in slip or stick-slip conditions with short or long stimulus duration (0.5 and 2 second). The results indicated that participants could better distinguish the direction with slip conditions than stick-slip conditions whereas the stimulus duration didn't have an effect on the accuracy. Thus, due to its higher perceptibility, we chose shear under the slip condition for the main experiment (i.e., less than 1 N of normal force in Fig. 4e). Finally, we had two users tune the rotational speed to match the perceived intensity to that of the vibrations and pressure resulting in a rotational speed of 1440 RPM.

4 USER EVALUATION

The objectives of the user evaluation were mainly twofold: validate the perceptibility of VPS tactile stimuli and better understand how users perceive them. To test the perceptibility or information transfer of VPS display, we first measured users' ability to identify different combinations of vibration, pressure, and shear with one VPS taxel. To gain better insights into how people perceive VPS stimuli, we performed three additional exploratory studies: two of which investigated pleasantness of each combination of VPS for a single taxel and for an array, and one study to measure the perceived continuity of different haptic combinations generated by an array of VPS taxels.

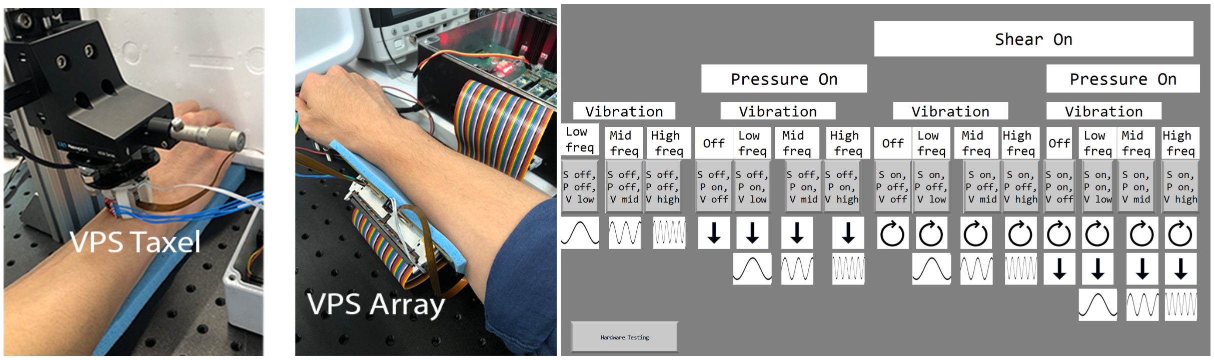
4.1 Study 1: Information Transfer and Identification Accuracy of VPS Taxel

The main question that we want to address is whether VPS Taxel can provide distinct and distinguishable tactile stimuli by combining vibration, pressure, and shear similar to RGB LED.

4.1.1 Hypotheses. With additional tactile dimensions, we hypothesize that the information transfer bandwidth will increase significantly and proportionally to the number of tactile dimensions [39]. We have designed VPS display such that each VPS dimension is independently controlled and aimed to stimulate different types of mechanoreceptors within the human's skin. Thus, we conjecture that users can process information even if multiple dimensions are activated simultaneously at the same location albeit with some loss in the identification accuracy.

4.1.2 Stimuli Set. With VPS display, there are three distinct tactile dimensions: vibration, pressure, and shear. However, VPS display can also render combinations of these tactile dimensions. Thus, we included all seven possible combinations to the stimulus set: vibration, pressure, shear, vibration + pressure, vibration + shear, pressure + shear, and vibration + pressure + shear. Due to the actuators in VPS display, it is possible to generate a wide range of differentiable vibrations while it is difficult to do so for pressure and shear. Thus, in addition to different tactile dimensions, we also incorporated and tested three frequencies of vibration (20, 70, 200 Hz), resulting in 15 stimuli in total.

4.1.3 Participants. Seven participants (Ages 25-55, 5M/2W) participated in this experiment. All of them were employees of the company. Two participants were familiar with the VPS display, 4 had some experience with



(a) Setup for user evaluation: for studies 1-2 (left) and for studies 3-4 (right).

(b) Stimuli selection stage for Study 1 where pictorial representations of each stimulus along with text descriptions are shown.

Fig. 5. (a) shows the setup for studies 1-4 and (b) demonstrates the stimuli selection stage for study 1.

haptic devices, and 1 had little or no experience with haptic devices. None had neurological disorders, injuries to the hand/arm, or any other conditions that may have affected their performance in this experiment.

4.1.4 Procedure. Participants were instructed to place their arm on top of the support foam and the VPS Taxel was loaded onto the dorsal side of the forearm near the wrist as shown in Fig. 5a. We fine-tuned the loaded normal force to be 0.3N to ensure slip for the shear stimulus. Then, we provided instructions to the subject before giving them noise canceling headphones to eliminate any audio cues.

Participants were given 3 minutes to explore and become familiar with all of the possible stimuli. Then, they moved onto a practice session consisting of 5 trials followed by the actual experiment with a total of 90 (15 stimuli x 6 repetitions) trials. In each trial, participants experienced one random tactile stimulus. Their task was to identify the stimulus by clicking the corresponding illustration on the screen as shown in 5b. Each stimulus lasted for 500 ms.

4.1.5 Data Analysis. For the identification study, the information transfer in bits was computed as in [42]:

$$IT_{est} = \sum_{j=1}^{K} \sum_{i=1}^{K} \frac{n_{ij}}{n} log_2 \frac{n_{ij} n}{n_i n_j}$$

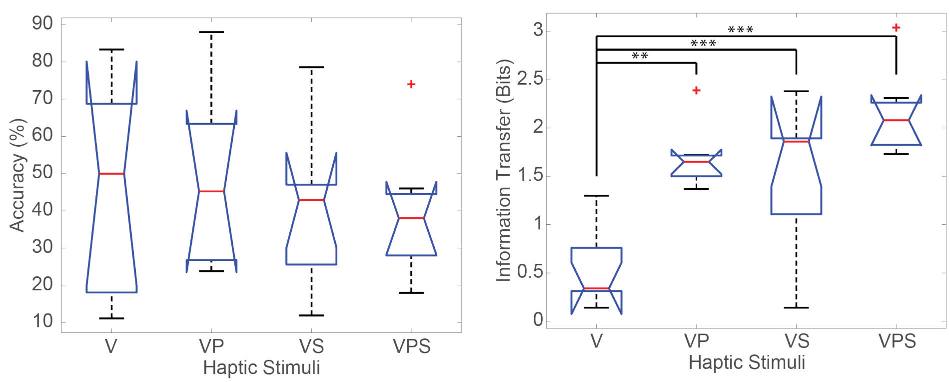
where K is the number of stimuli, n is the number of trials, n_i is the number of trials where stimulus i appeared, n_j is the number of trials where response j was given, and n_{ij} is the number of trials where stimulus i was responded to by response j.

For this study, we aim to study how the identification accuracy and information transfer (IT) change with additional tactile dimensions (pressure and shear) compared to the traditional vibrations alone. Thus, we first ran Anderson-Darling tests to confirm that the data follows a normal distribution and performed a 1-way repeated measures ANOVA to compare the means of identification accuracy and information transfer with each added modality as shown in Figure 7. Condition V includes vibrations only while condition VP includes all combinations of vibrations and pressure, including P (pressure only). Similarly, condition VS includes all combinations of vibrations and shear, including shear only condition. Finally, condition VPS include all combinations of vibrations, pressure, and shear (all 15 stimuli).

Perceived Stimulus

Actual Stimulus			Shear Off							Shear On							
			Pressure Off			Pressure On				Pressure Off				Pressure On			
			Vibration			Vibration				Vibration				Vibration			
			Low	Mid	High	Off	Low	Mid	High	Off	Low	Mid	High	Off	Low	Mid	High
Shear Off	Pressure Off	Low	8	3	0	0	10	4	0	2	6	1	0	2	4	2	0
		Mid	6	20	3	0	1	2	1	1	4	2	1	0	0	1	0
		High	3	11	23	0	1	1	0	0	1	0	1	1	0	0	0
	Pressure On	Off	0	0	0	40	0	0	0	1	0	0	0	1	0	0	0
		Low	3	1	0	3	15	3	0	2	3	1	1	4	4	1	1
		Mid	1	10	2	0	3	15	1	0	2	1	0	0	2	4	1
		High	0	7	12	0	0	0	13	0	0	3	0	0	2	0	5
Shear On	Pressure Off	Off	0	0	0	0	0	0	0	32	9	0	0	1	0	0	0
		Low	2	2	0	1	0	2	0	4	7	10	2	2	6	4	0
		Mid	0	4	0	0	0	4	2	0	4	19	3	0	3	3	0
		High	1	1	6	0	1	2	8	0	0	7	9	1	1	0	5
	Pressure On	Off	0	0	2	0	2	0	0	5	6	4	0	15	6	2	0
		Low	0	0	0	0	2	3	1	2	5	4	0	6	14	4	1
		Mid	0	7	1	0	2	9	0	0	7	3	1	0	1	9	2
		High	0	3	11	0	0	3	7	0	0	2	6	0	0	4	6

Fig. 6. Confusion Matrix from the Identification Task



(a) Identification Accuracy

(b) Information Transfer

Fig. 7. Identification Accuracy and Information Transfer from Identification Task

We have calculated the IT in V condition (and subsequently in VP and VS conditions) by only selecting the corresponding cells of the confusion matrix in Fig. 6. This method estimates the likelihood of IT with limited entropy in the stimulus set and omits confusion cells between V and S, and V and P. The drawback of this approach is that it gives a conservative estimate of IT ([7], chapter 2) as many trials are omitted due to cross-modal confusion and analysis was done with fewer trials.

4.1.6 Results. The combined 15x15 stimulus-response confusion matrix for all participants is shown in Table 6. The identification accuracy (IA) and information transfer (IT) for vibration alone (V) [IA:44%, IT:0.56], vibration + pressure (VP) [IA:47%, IT:1.69], vibration + shear (VS) [IA:40%, IT:1.52], and vibration + pressure + shear (VPS) [IA:39%, IT:2.15] are shown in Fig. 7 ($^{*}: p < 0.05, ^{**}: p < 0.01, ^{***}: p < 0.001$). No statistical significance was found for identification accuracies between conditions. On the other hand, the information transfer increases significantly from 0.56 bits up to 2.15 bits with additional tactile dimensions, confirming our hypothesis.

Two participants who were familiar with VPS display performed better than others for this identification task (72% vs. 45%). However, the trends between the different conditions (V,VP,VS,VPS) where accuracy decreases with additional tactile dimensions were still similar between the two groups. This suggests that while more exposure to VPS may improve the overall identification accuracy, users will still struggle with additional tactile dimensions.

4.2 Study 2: Perceived Pleasantness of a Single VPS Taxel

In the following three studies, we aim to evaluate the quality of the VPS both in isolation and in combination in terms of perceived pleasantness and continuity. We first investigate the perceived pleasantness of a single VPS taxel.

4.2.1 Hypotheses. As prior works have shown that vibration of lower frequencies are perceived as more pleasant [16], we hypothesize that even when combined with other tactile dimensions, stimulus combined with lower frequency vibration will be perceived more pleasantly than when combined with higher frequency vibration. Since shear and pressure also operate on a frequency similar or lower than that of the low vibration (20Hz), we hypothesize that shear and pressure will have similar or higher perceived pleasantness than that of low frequency vibration.

4.2.2 Stimuli Set. We used the same set of 15 different tactile stimuli as in study 1.

4.2.3 Procedure. After completing the stimulus identification (Study1), the same seven participants rated the pleasantness of the same set of stimuli on a scale from -7 to 7 (unpleasant to pleasant). There were a total of 45 (15 stimuli x 3 repetitions) trials for this study with each stimulus provided for 500 ms.

4.2.4 Data Analysis. To examine the effects of the three independent variables (Vibration, Pressure, and Shear) including interaction effects, a Mauchly's Test of Sphericity followed by a 3-way repeated measures ANOVA were performed for each dependent variable. If Mauchly's Test of Sphericity is violated, a Greenhouse-Geisser correction was used to calculate the F and p values from ANOVA. If any independent variable or combinations had statistically significant effects ($p < 0.05$), Bonferroni-corrected post-hoc tests were performed to determine which pairs of means are significantly different. The effect size (η_p^2) is also reported for statistically significant effects. For comparison, $\eta_p^2 = 0.01, 0.059, 0.138$ correspond to small, medium, and large effect size [6, 28].

4.2.5 Results. Fig. 8 shows the average pleasantness ratings and standard errors for each haptic combination generated by a single VPS Taxel. Haptic stimuli that are significantly different than zero are denoted ($^* : p < 0.05, ^{**} : p < 0.01, ^{***} : p < 0.001$). No combination of VPS violated the Mauchly's Test of Sphericity. The results show that the presence of shear reduces the pleasantness ($F(1, 6) = 12.95, p = .0005, \eta_p^2 = 0.123$), rejecting our hypothesis that shear will have similar perceived pleasantness as pressure or low frequency vibration. Also, our hypothesis that stimuli combined with low frequency vibration will be more pleasant than those combined with higher frequency vibrations is not confirmed.

4.3 Study 3: Perceived Continuity of a VPS Array

4.3.1 Hypotheses. We hypothesize that when the taxels in the array are sequentially activated, the shear dimension will be perceived as more continuous than other dimensions as it matches more closely with the lateral sensations of a sliding hand felt while stroking. On the contrary, due to the perpendicular direction of pressure with respect to the skin, we hypothesize that pressure will have the lowest continuity ratings for stroking gestures.

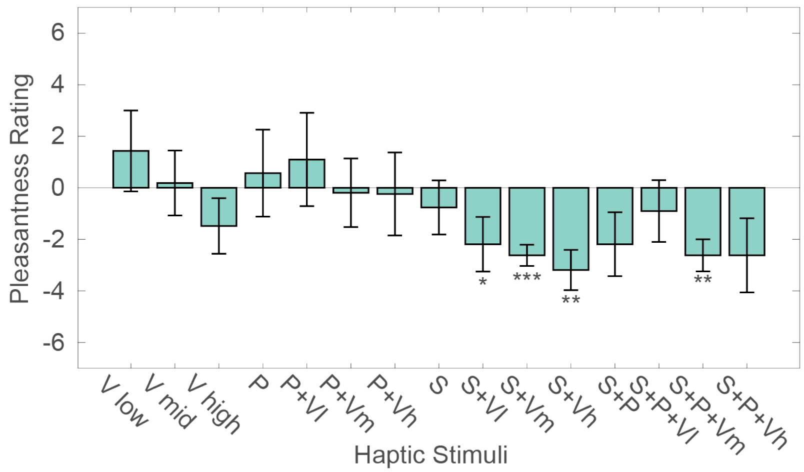


Fig. 8. Pleasantness of a single VPS Taxel

4.3.2 Stimuli Set. For the array, we included two stroke speeds (7 cm/s and 14 cm/s) as prior works have found the stroke speeds to have a significant effect on its perceived continuity and pleasantness [16, 27]. The two values were decided based on the preliminary testing where one felt slow and the other felt fast. For the ratio between stimulus duration and inter-taxel delay ($d = 1.302s, SOA = 0.266s$ for slow speed, and $d = 0.605s, SOA = 0.148s$ for fast speed), we used the optimal ratio found in prior work for different frequencies of vibrations [16]. As we saw little difference between middle (70 Hz) and high frequency vibration (200 Hz), we removed the middle frequency vibrations (70 Hz) and only provided low and high frequency vibrations (20, 200Hz). This led to a total of 22 possible tactile stroke stimuli.

4.3.3 Procedure. The same seven participants laid their forearm on the top of the VPS display as shown in Fig. 5a such that the stimuli are provided on the ventral side of the arm instead of the dorsal side. For this study, they rated the continuity of different strokes on a scale from 1 to 7 for a total of 66 (22 stimuli x 3 repetitions) trials. Each stroke lasted for either 2.1 seconds or 1.05 seconds based on the stroke speed.

4.3.4 Data Analysis. To examine the effects of the four independent variables (Vibration, Pressure, Shear and Speed) including interaction effects, a Mauchly's Test of Sphericity followed by a 4-way repeated measures ANOVA was performed for each dependent variable. Same statistical analysis was performed as in Study 2.

4.3.5 Results. The average continuity ratings of each haptic stimuli with their standard errors are shown in Fig. 9. No combination of VPS violated the Mauchly's Test of Sphericity. The presence of pressure significantly decreased the perceived continuity ($F(1,6) = 80.1, p = .003, \eta_p^2 = 0.193$) while the presence of shear significantly improved it ($F(1,6) = 12.89, p = .011, \eta_p^2 = 0.152$) confirming both of our hypotheses. On the other hand, the speed of the stroke did not significantly impact the perceived continuity. Overall, the perceived continuity for the VPS array is the highest when only the shear stimulus is provided. We also observed an interaction effect between shear and vibration ($F(2,12) = 5.3, p = .006, \eta_p^2 = 0.071$). Specifically, when combined with high frequency vibration, the presence of shear did not affect the perceived continuity.

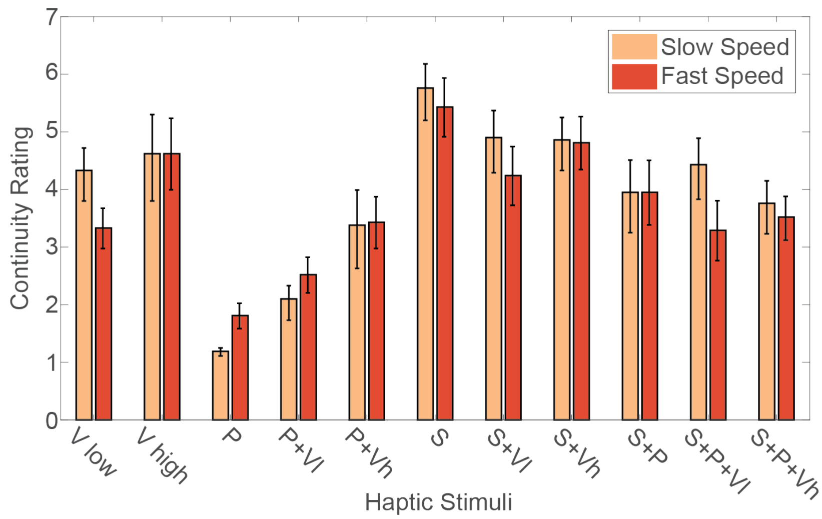


Fig. 9. Continuity of a VPS array

4.4 Study 4: Perceived Pleasantness of a VPS Array

4.4.1 Hypotheses. As a stroke gesture is one of the more pleasant gestures [47], we hypothesize that shear dimension will be perceived as more pleasant and continuous than other dimensions as it matches more closely with the sensation and direction felt while stroking. On the contrary, due to the perpendicular direction of pressure with respect to the skin, we hypothesize that pressure will have the lower pleasantness ratings.

Prior works demonstrate brushing velocities of 1-10 cm/s stimulate CT afferents most vigorously [26]. Thus, we hypothesize that the slow speed (7 cm/s) will be perceived as more pleasant and continuous than the fast speed (14 cm/s).

4.4.2 Stimuli Set. We used the same set of 22 possible tactile stroke stimuli as in Study 3.

4.4.3 Procedure and Data Analysis. Similar to study 3, the same seven participants laid their forearm on the top of the VPS display as shown in Fig. 5a. They rated the pleasantness of different strokes on a scale from -7 to 7 for a total of 66 (22 stimuli x 3 repetitions) trials. Similarly, the same data analysis was done as in Study 3.

4.4.4 Results. Fig. 10 shows the average pleasantness ratings and standard errors for each haptic combination generated by a VPS array. Haptic stimuli that are significantly different than zero are denoted ($^{*}: p < 0.05, ^{**}: p < 0.01, ^{***}: p < 0.001$). The presence of pressure decreased the pleasantness ($F(1,6) = 5.93, p = .016, \eta_p^2 = 0.041$) confirming our hypothesis on pressure. Similar to study 3, the stroke speed did not have significant impact on pleasantness rejecting our hypothesis while shear-only haptic stimuli had the highest pleasantness rating. It's interesting to note that it was the only stimuli with a positive rating.

4.5 Discussions

As we hypothesized, we saw lower identification accuracies with additional tactile dimensions although they did not vary significantly (average identification of 44%). On the other hand, we saw the expected significant increase in information transfer from 0.56 bits with vibrations-only (3 frequencies) to 2.15 bits with combinations of vibration, pressure, and shear. This partially validates our first hypothesis in that we can increase the information

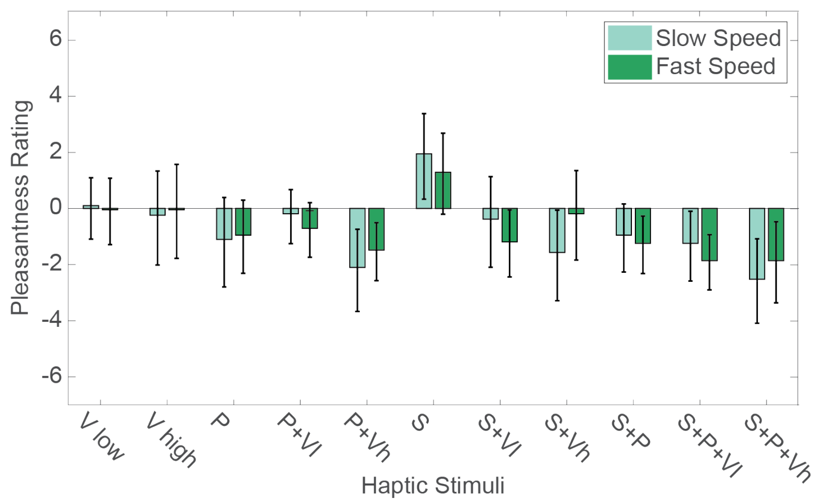


Fig. 10. Pleasantness of a VPS array

bandwidth with additional haptic dimensions. However, the increase is not linear as we didn't observe a significant difference between VP/VS and VPS (7b). This suggests that with VPS display, while we can stimulate different types of mechanoreceptors within our skin and increase the information transfer bandwidth with additional haptic dimensions, there may be an upper limit on the total amount of information people can receive on a small area of the skin. As the participant size for this study is rather limited, further investigations with a larger participant pool will be needed to confirm this.

In general, the identification accuracies were low. Even when only vibrations were presented, the average accuracy was approximately 50%. This suggests that the three test frequencies may not have been distinct enough to begin with and that either fewer vibration frequencies or frequencies with larger gaps may increase the identification accuracies for both vibration alone and combinations of VPS. Further studies will be needed confirm this. Despite the lower identification accuracy, the study still confirms our hypothesis that the information transfer increases with additional tactile dimensions and with non-significant loss in accuracy, thus suggesting the practicality of additional tactile dimensions.

Low frequency vibrations were highly confused with the same vibrations combined with another dimensions, such as P+Vl, S+Vl and S+P+Vl, and some confusion with the mid frequency stimuli. However it was rarely confused with pressure-only cues or high frequency stimuli. Mid frequency stimulus was mainly confused with low and/or high frequency stimuli, and high frequency vibrations were frequently confused with the mid frequency stimuli. These confusions indicated skin's poor acuity to resolve frequency of vibrations especially in the presence of masking stimuli, and the confusion errors decreased when the stimulation frequencies were separated apart, as indicated in [43]. Both pressure and shear cues were well identified in isolation, however their combinations with other cues yielded confusions, indicating that the three VPS dimensions of tactile perception may not be indeed completely independent, as also shown in [9].

For a stroke gesture, presence of shear significantly improved the perceived continuity as we expected while the shear only stimuli had the highest pleasantness rating. It is interesting to note that while shear only stimuli had a positive pleasantness, when combined with other dimensions, the perceived pleasantness decreased. This may suggest that when combining different dimensions, it is critical to design them together such that they complement each other. Otherwise we may observe a phenomenon similar to the uncanny valley of haptics in which the subjective impression of realism got worse when the fidelity of visual and haptic sensation didn't increase in concordance [3].

Contrary to the perception of a stroke gesture, shear from a single taxel had negative effect on pleasantness even when presented alone. Some participants provided informal feedback that for a single taxel, they felt their hairs being entangled and thus felt unpleasant. The discrepancy may also be due to the fact that during a stroke gesture, the direction of the shear stimuli matched the direction of the stimuli sequence, thus perhaps activating CT afferents (CTA) which are responsible for conveying 'pleasant touch' through the skin [26].

As we hypothesized, presence of pressure significantly decreased both the perceived continuity and pleasantness during stroke gesture. The perceived continuity and pleasantness may be improved by using custom pressure profiles with gradual onsets and decays, similar to how Culbertson et al. have done rather than a sudden step profile [8].

The pleasantness and continuity ratings for an array shows that speed has no significant effect on both. This suggests that the optimal ratio of duration (d) and inter-taxel delay (SOA) determined in [16] for continuous tactile strokes may be valid not only for vibrations but also for shear strokes. Further investigations will be needed to confirm this.

5 LIMITATIONS & FUTURE WORK

While we selected actuators for VPS display due to their compact size, there are certain limitations, especially for pressure and shear. As voice coils are typically designed to generate vibrations, the range of pressure that can be generated with voice coils is less ideal than actuators intended for pressure such as linear actuators. If a stronger actuator is used for pressure in the future, we could potentially further increase the information transfer, perceived pleasantness, and perceived continuity. For shear, the force is limited by the selected DC motor's maximum torque. Thus, if a higher torque motor had been used, we would have been able to generate skin-stretch stimuli. This could have been incorporated into the user study to better understand its perceptibility, pleasantness, and continuity.

Due to the actuators used for pressure and shear, we only tested binary values for pressure and shear. In the future where the VPS taxel consists of actuators with a wider range of force and displacement, we could test each dimension and combinations of them with more values for all vibration, pressure, and shear. This would allow even higher information transfer and potentially higher perceived pleasantness and continuity.

For studies 3 and 4 where we evaluated an array of VPS taxels, we used the same stimuli that were in study 1 and 2 for a single VPS taxel. However, if we used different profiles such as ones with fade-in and fade-out, the results could have been better both in terms of its perceived pleasantness and continuity. For instance, Culbertson et al. used an initial retraction followed by a quadratic profile [8].

In the future, we would like to conduct an elicitation study to explore how people use VPS display and what types of information could be communicated. Specifically, it would be interesting to see if users tend to prefer particular tactile dimensions or combinations to convey a specific message.

The size of the actuator presented in the paper can be further reduced, by limiting the output to noticeable levels and removing unnecessary components from off-the-shelf actuators. Moreover, these actuator taxels can be placed in watches or wristbands, and may be used in a sleeve in an array form. These form-factors and actuator configurations will be further explored in the future studies.

To increase the tactile dimension further, thermal rendering could also be added similar to [21] where a peltier element is added. The addition of thermal display may not only increase the tactile information transfer but also improve the ability to convey positive affection as warmth has been found to be associated with pleasantness [12, 36].

6 CONCLUSION

In this paper, we sought to improve the information bandwidth of tactile devices by combining vibration, pressure, and shear. With our multi-dimensional tactile device, VPS display, we evaluated its performance with regard to each of its tactile dimensions and ran user studies to demonstrate that although the simultaneous tactile cues reduce identification accuracy, additional tactile dimensions widen the range of information transfer. Additional exploratory studies revealed that shear stimuli generated in an array provide the most continuous and pleasant sensations. We hope that our results will help inform haptic designers about multi-dimensional haptics and inspire them to investigate it further.

ACKNOWLEDGMENTS

This work was supported by Facebook, Inc and we would like to thank Jennifer Chen, Hieu Nguyen, and Frances Lau for valuable technical support and guidance.

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Received February 2019; revised April 2019; accepted April 2019