HyVE – Hybrid Vibro-Electrotactile Stimulation – is an Efficient Approach to Multi-Channel Sensory Feedback

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HyVE – Hybrid Vibro-Electrotactile Stimulation – is an Efficient Approach to Multi-Channel Sensory Feedback

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***Abstract*—An important reason for the abandonment of commercial actuated hand prostheses by the users is the lack of sensory feedback. Wearable afferent interfaces capable of providing electro- or vibro-tactile stimulation have high potential to restore the missing tactile and/or proprioceptive information to the user. By definition, these devices can elicit single modality (i.e. either vibrotactile or electrotactile) substitute sensations. In a recent research we have presented a novel approach comprising hybrid vibro-electrotactile (HyVE) combined stimulation, in order to provide multimodal sensory feedback. An important advantage of this approach is in the size of the design: the HyVE interface is much more compact than two separated single-modality interfaces, since electro- and vibro-tactile stimulators are placed one on top of the other. The HyVE approach has been previously tested in healthy subjects and has shown to provide a range of hybrid stimuli that could be properly discriminated. However, this approach has never been assessed as a method to provide multi-channel stimuli, i.e., stimuli from a variety of stimulators, mapping information from a multitude of sensors on a prosthesis. In this study, the ability of ten healthy subjects to discriminate stimuli and patterns of stimuli from four different five-channel interfaces applied on their forearms was evaluated. We showed that multiple HyVE units could be used to provide multi-channel sensory information with equivalent performance (~ 95% for single stimuli and ~ 80% for pattern) to single modality interfaces (vibro- or electro-tactile) larger in size and with better performance than vibrotactile interfaces (i.e., 73% for single stimuli and 69% for pattern) with the same size. These results are promising in relation to the current availability of multi-functional prostheses with multiple sensors.**

***Index Terms*—sensory substitution, vibrotactile, electrotactile, hybrid stimulation, haptic devices, multi-channel feedback discrimination, upper limb prosthetics.**

I. Introduction

MODERN, electrically-powered prosthetic hands are sophisticated mechanical systems with individually controllable fingers and with the mass and size similar to a human hand (e.g., i-Limb from Touch Bionics, BeBionic Hand from RSL Steeper [1], [2] etc.). With this flexibility and with a stable and robust human-machine interface (i.e. myoelectric control) different control strategies can be implemented and the grasping function lost after an amputation can be partly restored. However, in addition to the motor dexterity, the biological hand supplies humans with rich proprioceptive and exteroceptive sensory feedback, which is instrumental in achieving seamless and effective reaching and grasping [3]. Nevertheless, none of the commercially available myoelectric prostheses implements any kind of somatosensory feedback. This affects the overall efficacy of the device and decreases the acceptance rate among target users. For example, a large proportion of amputees opt for the less sophisticated body-powered prostheses, since these systems provide intuitive kinesthetic feedback through the control cables [4].

In principle, to restore the missing sensory information, a prosthesis could be instrumented with artificial sensors able to record different touch modalities (touch, pressure, vibration, and temperature) as well as proprioception and such information could be processed and delivered to the user in a physiological or close-to-physiological manner. To achieve this challenging goal, various approaches were investigated over the years and interesting review studies of the field were published [5]-[8]. Some of these methods made use of invasive surgical procedures and relied on direct electrical stimulation of sensory neural structures which are physiologically involved in the task, using implantable electrodes [9], [10]. Some other approaches grounded on non-invasive wearable technologies and exploited the concept of *sensory substitution*, in which the feedback information is delivered by stimulating substitute neural structures, i.e., sensory organs that are different from the ones normally involved in the task (e.g., stimulating the skin on the chest or the residual limb). Some sophisticated haptic devices that are able to stimulate the user with the same sensory modality recorded by the prosthesis (e.g., grasping *pressure* conveyed as a *pressure* on the skin) have been developed, thereby allowing an effortless association between the recorded and delivered stimulus [11]- [13]. However, the most common and simplest methods are those that employ vibrotactile or electrotactile (electrocutaneous) stimulation to activate the tactile sense (e.g., grasping *pressure* conveyed as a *vibration* on the skin) [14].

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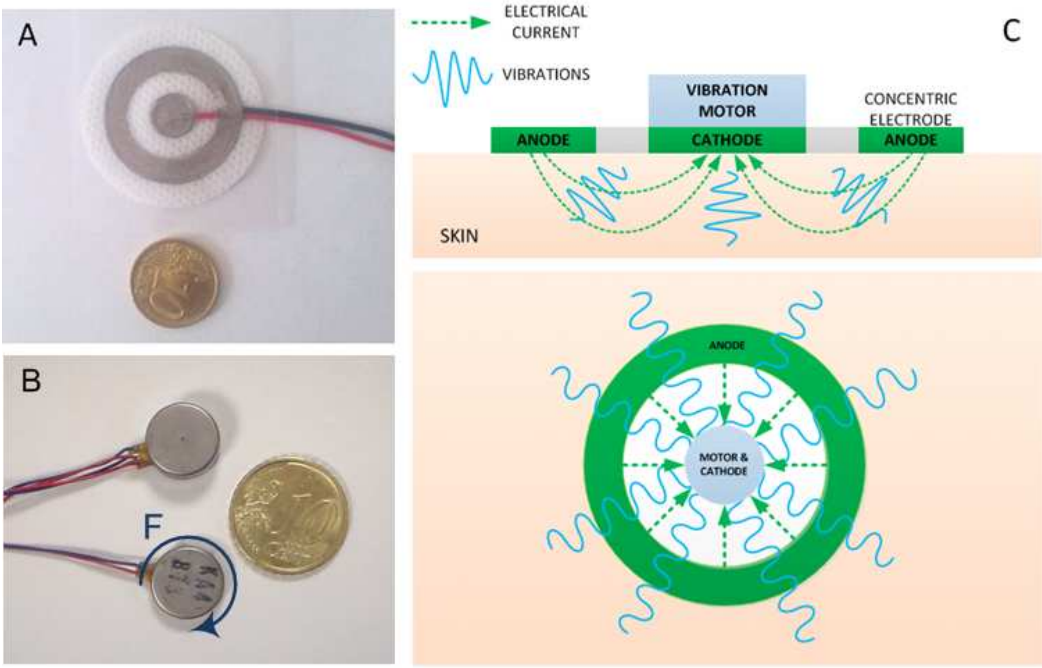

Fig. 1. Stimulation devices: A) concentric electrode for electrocutaneous stimulation, B) a coin-type vibration motor, and C) HyVE interface. In the latter, the stimulation and vibrations are delivered simultaneously and to the same location on the skin.

Vibrotactile interfaces can be built with extremely simple components. Indeed a mechanical vibration can be generated using small, coin type vibration motors that are nowadays used in mobile phones (Fig. 1B). These are miniature DC motors with an eccentric mass attached to the rotor shaft. The rotation of the eccentric mass produces unbalanced centrifugal forces, which cause the whole motor to vibrate and hence the body on which it is physically connected. The vibration intensity and frequency can be varied by modulating the current that flows into the motor. Electrotactile interfaces can also be very simple. Low level current pulses generated by an electrical stimulator can be delivered to the body using, for example, concentric electrodes (Fig. 1A). In this case, the current flows between the inner and outer ring of the electrode, eliciting a well-focused, superficial sensation. Most importantly, both vibro- and electro-tactile interfaces are convenient for the integration into the prosthetic socket because they are small sized, low cost and energy efficient [14]-[17]. Therefore they have been considered as potential solutions for providing sensory feedback in prostheses. Vibrotactile and electrotactile devices were investigated separately in a number of studies in the past [17]-[26]. Recently we have proposed the integration of these two stimulation methods in the form of a novel hybrid vibro-electrotactile (HyVE) interface, providing electro- and vibro-tactile stimulation simultaneously and to the same location on the skin [27]. The HyVE was implemented by placing a vibration element (vibel) over the cathode of a concentric electrode connected to an electrical stimulator (Fig. 1C). We performed psychophysical tests on a single site on the forearms of healthy subjects and we demonstrated that they were able to independently discriminate the properties of the two individual stimuli within the hybrid stimulus. Briefly, this implies that a single HyVE stimulator implements a multimodal feedback channel in which two concurrent information streams flow through the same site on the skin to provide afferent information.

In the present work we evaluated the possibility to exploit HyVE stimulation to deliver multi-channel sensory information to the skin using a number of stimulation points spatially distributed across the forearm. The underlying reason for this study is that multi-fingered prostheses endowed with artificial tactile sensibility are progressively becoming a reality and sensory feedback systems able to convey multi-source, spatially distributed afferent information are thus necessary. An important advantage of the hybrid approach is in the size of the design: as the vibrators and electrodes share the same space, the HyVE interface is much more compact than a single-modality interface with the same number of channels. Since the space available within a prosthetic socket is limited, smaller space occupancy is a clear advantage.

The state of the art of multi-channel, non-invasive stimulation techniques applied to prosthetics is relatively poor; this is likely due to the fact that simple one degree of freedom prostheses have been the only clinically viable option for the past forty years. Nevertheless, designs or prototypes can be found in the prosthetics and biomedical engineering literature. One of the most clever concepts is the solution proposed by Rosset (1916) in which a pneumatic system composed of pressure pads and a tube transmitted pressure from the fingers of the prosthesis to the residual limb, directly [5]. This concept was further investigated and implemented (6 channels) using the phantom hand map as the target for sensory feedback by Antfolk et al. [28]. Bach-Y-Rita and Collins proposed concepts where arrays of vibrotactile stimulators would convey proprioceptive information on the back or on the

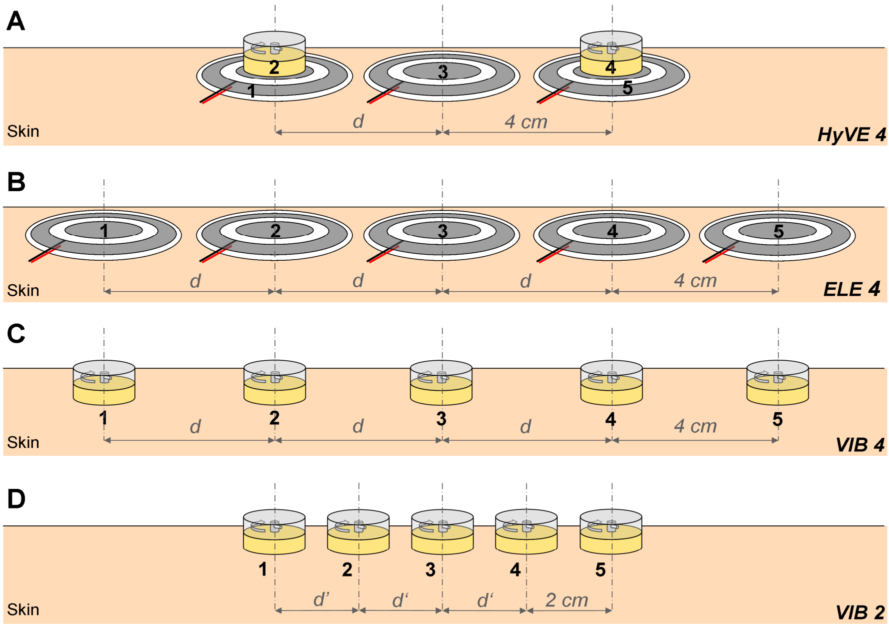

Fig. 2. Four stimulator configurations tested in this study: A) HyVE4: two HyVE interfaces and one concentric electrode with a center to center distance equal to d = 4 cm and a total length of 8 cm; B) ELE4: electrocutaneous concentric electrodes with a center to center distance equal to d = 4 cm and a total length of 16 cm; C) VIB4: vibration motors with a center to center distance equal to d = 4 cm and a total length of 16 cm; D) VIB2: vibration motors with a center to center distance equal to d' = 2 cm and a total length of 8 cm. The numbers from 1 to 5 depict the channel numbering.

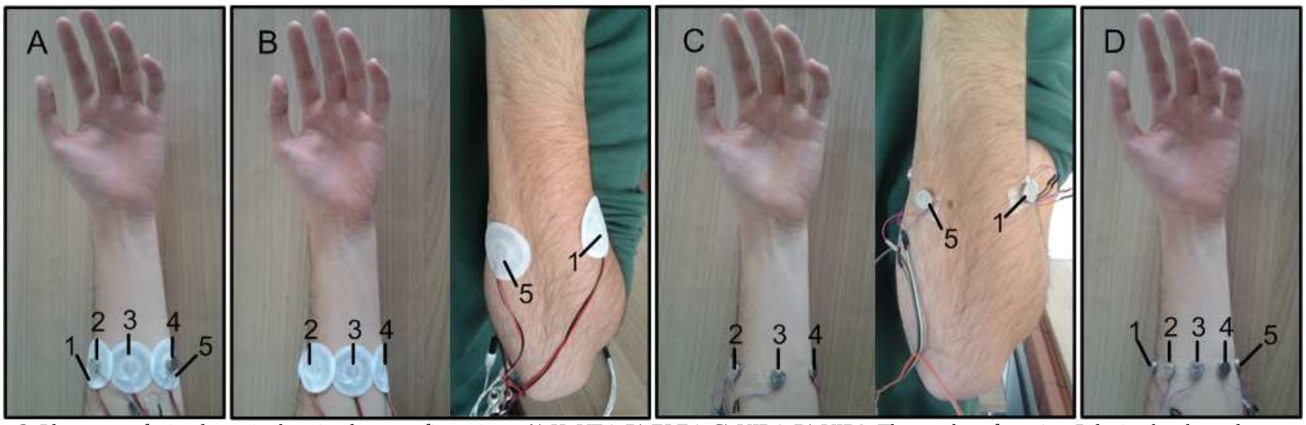

Fig. 3. Placement of stimulators in the stimulator configurations: A) HyVE4; B) ELE4; C) VIB4; D) VIB2. The numbers from 1 to 5 depict the channel numbering.

stump of the amputee [29]. Mann et al. detailed a system where the elbow angle of the Boston Arm was fed back exploiting an array of vibrotactile stimulators [30]. Similarly and more recently, Saunders and Vijayakumar [20] used eight button-type vibrators placed along the volar side of the forearm to feed back the grasping force in the form of a stimulus location. Witteveen at el. [31], used vibrotactile and electrotactile arrays comprising eight motors and electrodes placed longitudinally and transversely along the forearm to provide proprioceptive feedback about the aperture of the hand. Antfolk at el. [12], [19] and Cipriani et al. [17], using arrays of pressure devices or arrays of vibrators in similar experiments, evaluated the ability of healthy subjects and amputees to locate one active channel (out of five) in the array (site discrimination) and to recognize six different spatial stimulation patterns simulating the finger contact information during six types of grasp.

No behavioral study involving real-life activities with a prosthesis touching or grasping objects was carried out previously, to our knowledge. However the general research outcome was promising, meaning that humans were able to learn and to associate visuo-tactile stimuli in psychophysical experiments. Importantly, all of the aforementioned studies used single-modality multiple stimulators and only in few cases they compared the differences between the modalities [19], [31]. Hence, the goal of the present study was twofold. The first goal was to evaluate the ability of healthy subjects to recognize multi-channel stimuli coming from the HyVE and to evaluate the novel hybrid interface against the conventional, single modality interfaces. The second goal was to test a number of single-modality interfaces, again, in terms of users' recognition ability in order to compare different modalities available for the implementation of the sensory substitution feedback (vibrotactile vs. electrotactile) and evaluate the influence of distance between the stimulation units in multi-channel recognition.

TABLE I
ACTIVATION PATTERNS MIMICKING CONTACT INFORMATION OF SINGLE FINGERS AND FIVE GRASPS

Test	Active channels	Channel pattern 1 2 3 4 5	Simulated action/grasp
Single channel discrimination (SD)	1	● ○ ○ ○ ○	Single finger contact (thumb)
	1	○ ● ○ ○ ○	Single finger contact (index)
	1	○ ○ ● ○ ○	Single finger contact (middle)
	1	○ ○ ○ ● ○	Single finger contact (ring)
	1	○ ○ ○ ○ ●	Single finger contact (little finger)
Pattern discrimination (PD)	1	● ○ ○ ○ ○	Lateral grip (tip of the thumb)
	2	● ● ○ ○ ○	Bi-digital grip (tip of the thumb and index)
	3	● ● ● ○ ○	Tri-digital grip (tip of the thumb, index and middle)
	4	● ● ● ● ○	Palmar for a smaller object (tip of the thumb, index, middle and ring)
	5	● ● ● ● ●	Palmar for a bigger object (i.e., tips of all the fingers)

Note: The "Channel pattern" column depicts the activity of the channels in five different SD and PD patterns (rows in the table) that were presented to the subjects. The empty or full circle denotes that the specific channel was off or on in the given pattern, respectively. The circles from left to right correspond to the channels from 1 to 5, as indicated below the "Channel pattern" title. The numbering corresponds to that used in Figs. 3 and 4.

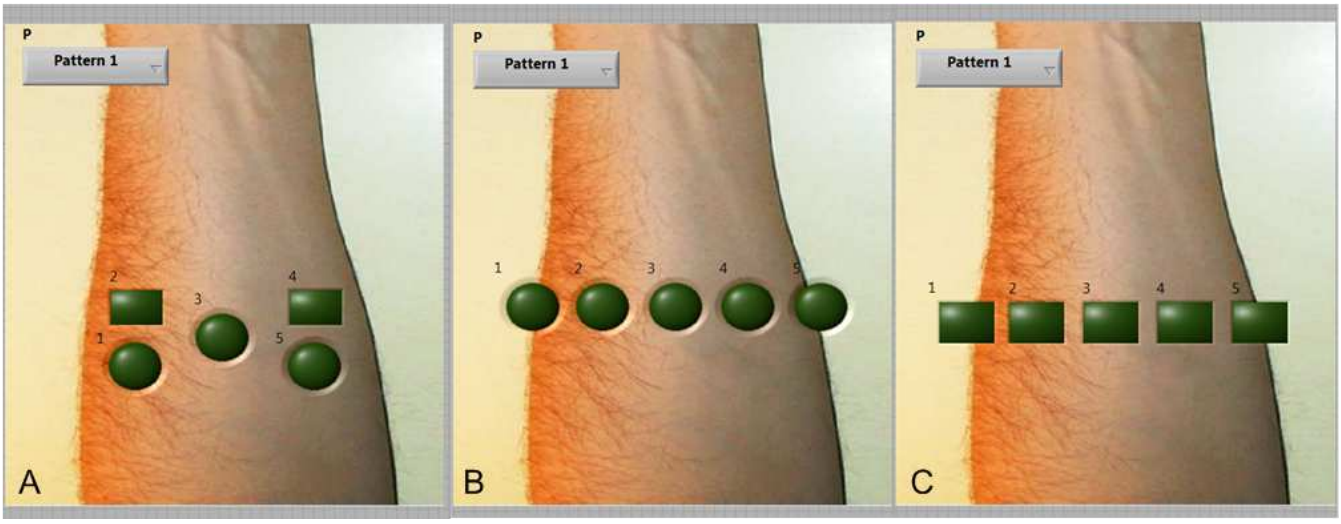

Fig. 4. Screens displayed to the participants during the learning phase: A) HyVE4 configuration; B) ELE4 configuration; C) VIB4 and VIB2 configurations.

II. MATERIALS AND METHODS

A. Five channel interfaces

This work focused on five-channel interfaces based on previous studies [12], [19]. The configuration fits well with the number of fingers of a sound hand and of new multi-fingered hands currently available: if each finger of the prosthesis would be equipped with one touch/pressure sensor, five channels would be required to convey the contact information back to the user.

The HyVE interface was implemented by combining vibrators and concentric electrodes (in turn connected to an electrocutaneous stimulator). The vibrators used were flat miniature vibration motors (Precision Microdrives, UK) (12 mm diameter, 3.4 mm height, 1.7 g mass) driven by a custom microcontroller board [17]. The electrodes were disposable, self-adhesive, 4 cm diameter, concentric electrodes (Spes Medica, Italy) connected to a multi-channel stimulator (TremUNA, UNA Systems, Serbia). The stimulation was current-controlled and biphasic with a square pulse to depolarize the fibers and an exponential relaxation phase to remove the injected charge from the tissue. Vibrators and electrodes were arranged as shown in Fig. 2A: two vibrators were placed on top of the cathodes of two electrodes (inner contact) forming two HyVE elements; a third electrode was placed in between, making a total of five stimulation channels (three electro- and two vibrotactile). The distance of 4 cm between the centers of the two consecutive electrodes (d in the picture) was dictated by their diameter. For simplicity we will refer to this interface as to *HyVE4*, hereafter. Our main hypotheses were that multiple HyVE units could be used to provide multi-channel sensory information with 1) an equivalent or better performance than a single modality interface with the same distance between the stimulating elements and hence larger overall size and 2) a better performance than a single modality interface with the same overall size (i.e., smaller distance between the stimulating elements).

In order to test our hypothesis, we compared *HyVE4* to three other configurations of five-channel single-modality interfaces. A five-channel electrotactile interface (hereafter called *ELE4*) was implemented using five concentric electrodes arranged in a line and with the same inter-electrode distance of *HyVE4* (i.e. d = 4 cm) (cf. Fig. 2B). Two different five-channel vibrotactile interfaces were implemented using five vibrators: one with d equal to 4 cm (*VIB4*) (Fig. 2C), and the other with *d'* equal to 2 cm (*VIB2*) (Fig. 2D). *VIB4* was implemented (and tested) in order to be directly comparable to *HyVE4* and *ELE4*, since *d* was equal to 4 cm in all three cases. Note that for the same number of channels the *HyVE4* configuration is more compact compared to *ELE4* and *VIB4*. The overall length of the HyVE4 array (i.e. the space taken) measured as the distance between the center of the first and the center of the last element is half the size of *ELE4* or *VIB4* ($2 \cdot d$ = 8 cm for *HyVE4* vs. $4 \cdot d$ = 16 cm for *ELE4* and *VIB4*). *VIB2* was implemented as a control condition for *HyVE4*, as in both cases the total length was equal to 8 cm.

The vibrotactile and electrotactile stimulators were connected to a host (laptop) and were controlled in real time by sending simple commands over a USB connection. For all configurations the vibro- and electro-tactile stimulators were activated at the lowest intensities possible. The lowest intensities were selected in order to elicit localized tactile sensations, minimizing the spread of vibrations through the skin and also generation of referred sensations in distal segments due to electrical stimulation of sensory nerve bundles. The frequency and intensity of mechanical vibrations produced by the vibrotactile interface were measured by means of a 6 axis load cell (nano43, ATI, NC, USA) [17]: the measured intensity was 0.46 N and frequency 120 Hz. The vibration intensity was above human perception threshold [14]. The lowest intensity for the electrotactile stimulator was set to 1.2·PT, with PT being the Perception Threshold, determined for each subject before the experiments started (cf. section C); the pulse rate was fixed at 100 Hz. This pulse rate was chosen since at high rates, i.e. ~ 100 Hz, electrical stimuli feel like constant pressure and hence can be more easily discriminated from a mechanical vibration [27].

B. Experimental protocol

The experimental protocol in this study was similar to those used in [17], [19], [27]. Ten able-bodied subjects (7 males, 3 females, 29±3 yrs) participated in the experiments, which were approved by the local ethics committee. Each of the four interfaces (order randomized among subjects) was placed at mid forearm transversely (Fig. 3) and for each interface two tests were performed one after the other: single channel discrimination (SD) and pattern discrimination (PD). The first test (SD) was aimed at evaluating the ability of healthy subjects to recognize single stimulus coming from one of the five channels. The second test (PD) was aimed at evaluating the ability in recognizing combinations of stimuli (i.e., patterns) from a subset of channels which were activated simultaneously. The patterns were chosen so that they simulated the contact information from the five fingers in daily-living grasps, thereby imitating the expected activation of the stimulation channels during grasps using a hand prosthesis equipped with individual contact/force sensors for each finger, as in [17]. A graphical description of the SD and PD tests is shown in Table I. The channels numbering and assignement are depicted in Table I and Figs. 3 and 4. The channels were assigned to the fingers so that the relative position of the channels over the forearm, from left to right, resembled the ordering of the respective fingers, as seen by the user. The left most channel (number 1) corresponded to the left most finger (thumb) and so on (Fig. 3 B, C and D). In HyVE4 (Fig. 3A), the channels 1 and 2, and 4 and 5 overlaped. Therefore, the spatial correspondence could not be as clearcut as in the single modality configurations, but it followed the same general principle.

The protocol had the same structure for the four configurations (interfaces) and it was comprised of three phases: learning with visual feedback, reinforced learning without vision and validation also without vision. In each phase subjects were exposed to sequences of stimuli (either a single channel or a pattern) that lasted 1 second. During the experiments the subjects wore earmuffs playing white noise in order to mask the noise generated by the vibration motors. In the learning phase participants received a visual feedback on a computer screen indicating the site/pattern (Fig. 4), while being stimulated. The participants were instructed to focus on the stimulation and to associate it to the visual description on the screen, i.e., filled circles representing the active channels superimposed on a picture of a forearm. In the reinforced learning phase the participant was blindfolded; after the presentation of each stimulus, he/she verbally indicated which stimulus he/she perceived and the experimenter stated the correct answer. During the final validation phase the participant verbally indicated the stimulus while no feedback was given. This session was used to validate the results of the learning and reinforced learning sessions. Each stimulus (site or pattern) was presented to the subject 12 times during the first two sessions and 7 times during the validation phase. Throughout the experiments the sites and patterns were randomly selected. The experimental session lasted about 2 hours in total.

C. Evaluation of the Perception Threshold prior to the experiments

Prior to the experiments we determined the Perception Threshold (PT) for each subject and stimulation site using the *method of limits* [32] by varying the pulse width (PW) of the stimulus. The pulse rate and intensity were set to 100 Hz and 3 mA, respectively. The PW was then increased in equidistant steps (10 µs) while the subject verbally indicated when he/she felt a slight sensation. We chose to vary the PW of the waveform instead of the current intensity since the former usually provides more accurate control of the elicited sensation. The test was repeated three times and the average value was adopted as the PT. During PD and SD experiments, the PW was set to 1.2·PT, whereas the pulse rate was fixed at 100 Hz and the current intensity at 3 mA.

D. Data processing

The performance metric was the recognition rate (RR), i.e., the percentage of stimuli correctly identified by the participants. The results are presented in the form of confusion matrices in order to highlight the overall recognition ability as well as the most prevalent mistakes. A one-way repeated measures ANOVA was used to compare the results of the tests

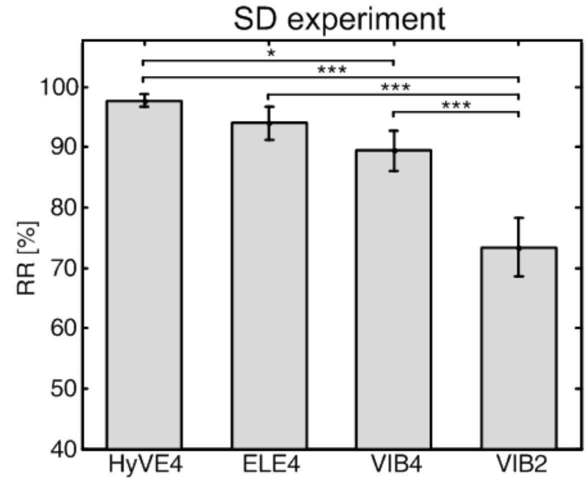

Fig. 5. Overall recognition rates (mean ± standard errors) obtained in the SD experiment (asterisks indicate statistical significant difference by post hoc analysis: * indicates p<0.05, *** indicates p<0.001).

for all configurations and identify possible statistically relevant differences in the RR of the stimuli using the different configurations. The assumption of sphericity was tested using Mauchly's sphericity test. In case of sphericity violation, we crosschecked the results of repeated measure ANOVA (rmANOVA) by running multivariate ANOVA (Wilks' test, mANOVA) for repeated measure design and also univariate ANOVA with Greenhouse-Geisser corrections (cANOVA). Finally, we have used Fisher LSD test for the post hoc pairwise comparisons. A paired two-tailed t-test was also used to compare the RR across learning and evaluation phases for each interface.

III. Results

All the results in this section refer to the validation phases of the experiments and are given in the form of mean ± standard deviation in the text and mean ± standard error in the figures.

A. SD experiment

Fig. 5 depicts the overall performance from all subjects and all interfaces tested. The RR of the different configurations was 98±3% for HyVE4, 94±9% for ELE4, 89±10% for VIB4 and 73±15% for VIB2. The Mauchly’s test showed that the data from the SD experiment violated the sphericity assumption ($p < 0.05$); however, the differences in RR among the four configurations resulted statistically significant in all statistical test ($F(3,27)=14.6$, rmANOVA, $p<0.001$; mANOVA, $p < 0.05$; cANOVA, $p < 0.001$). Post-hoc tests demonstrated that the RR of HyVE4 was statistically different from VIB4 ($p<0.05$) but not from ELE4. The RR for ELE4 was similar to VIB4 (no statistical difference). VIB2 was significantly different from the other three configurations ($p < 0.001$): most important, it was different from VIB4 (same stimulation modality but different inter-element distance d) and from HyVE4 (different stimulation modality but same overall length).

Fig. 6 shows the confusion matrices relative to the RR in the four configurations, from all subjects. For all systems, when misclassified, channels were primarily confused with adjacent ones. There were only a few unsuccessful trials using HyVE4, in which the subjects misrecognized channel 5 with 3 and vice-versa (neighboring electrodes) or channel 2 with 4 (the two vibrators). In ELE4 unsuccessful trials were limited to channels 4 and 3 that were misclassified with neighboring electrodes. With *VIB4* and *VIB2*, the subjects misrecognized all five channels with more errors for *VIB2*. In particular, with *VIB2* the performance varied significantly across the channels ($F(4,36)=7.4$, $p<0.001$) with those placed medially being worse recognized than those more lateral.

The RR during the validation phase increased in statistically significant way with respect to the reinforced learning phase only in the case of HyVE4 interface ($p < 0.05$). Therefore, the training did not significantly improve the performance in the other cases.

B. PD experiment

Fig. 7 depicts the overall performance in experiment PD from all subjects and all interfaces. The overall RR was lower than in the SD experiment. The RR of the different configurations was 79±13% for ELE4, 77±17% for VIB4, 77±6% for HyVE4, and 69±8% for VIB2. The RR across the four configurations was statistically different ($F(3,27)=3.0$, $p<0.05$). Post-hoc tests demonstrated that the performance was not statistically different for ELE4, VIB4 and HyVE4 ($p>0.05$). On the other hand VIB2 was significantly different from the other three configurations ($p<0.05$).

Fig. 8 shows the confusion matrices relative to the RR in the four configurations, by all subjects. The matrices have a structure similar to the SD experiment but with more frequent misclassifications. Generally, a pattern was misclassified with another that differed in only one active channel (“neighboring” patterns in Table I). In ELE4 and HyVE4, the most frequent mistakes were concentrated to patterns 3, 4 and 5; in addition, the RR across the different patterns was significantly different ($p<0.001$). With VIB4 and VIB2 misclassifications were spread across all patterns.

The RR during the validation phase did not increase or decrease in statistically significant way with respect to the reinforced learning phase.

IV. Discussion

In our recent study, we demonstrated that electro- and vibro-tactile stimulation modality can be combined in order to implement more effective information transfer using intensity modulation [27]. With a single HyVE interface we demonstrated that human subjects can independently recognize the intensities of the electro- and vibro-tactile stimuli that are delivered simultaneously within the hybrid stimulus. The main goal of the present study was to evaluate the possibility to exploit HyVE stimulation in order to deliver multi-channel sensory information to the skin of the forearm in a compact fashion. For this reason the ability of human subjects to discriminate the active sites and patterns of stimulation delivered by hybrid interfaces was compared to

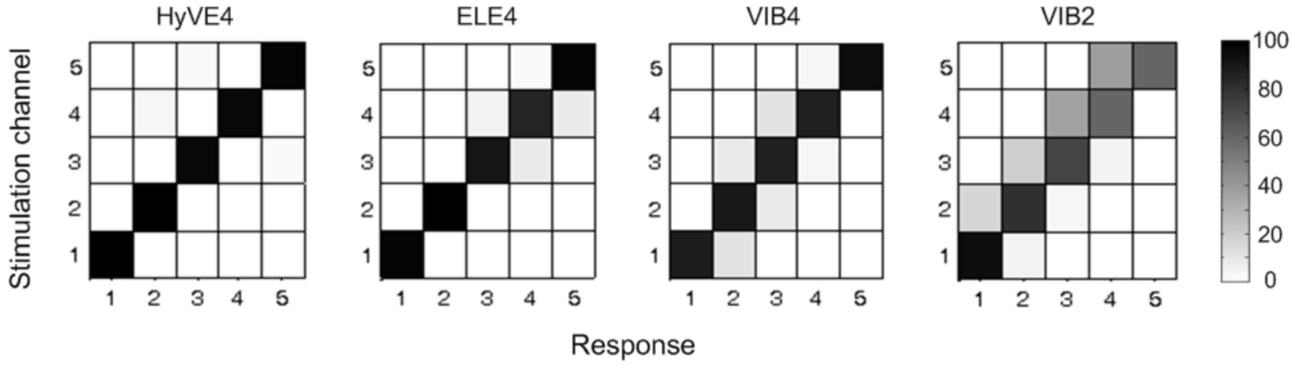

Fig. 6. Confusion matrices of the recognition rate obtained in the single channel discrimination experiment.

the discrimination ability of single modality- either electrical or vibratory- interfaces.

The results demonstrated that our hypostheses (see section II.A) about the performance with hybrid versus single modality interfaces were in fact correct. The RR of the hybrid interface (HyVE4) showed the smallest standard deviation (i.e. more consistent inter-subject and inter-channel RR) and was better or comparable to the bulkier (twice the size) single modality configurations (ELE4 and VIB4), in both SD and PD experiments. In addition, the RR of the compact single modality interface (i.e. VIB2) was significantly lower than for the hybrid interface, in both SD and PD experiments. Therefore, this study indeed demonstrated that multiple HyVE units could be used to provide multi-channel sensory information with better or equivalent performance to the single modality interfaces (vibro- or electro-tactile) larger in size (distance between centers of the first and of the last stimulating element) and with better performance than vibrotactile interfaces with the same size.

An important goal of this study was to evaluate the user's RR for different single-modality interfaces with varying sensory substitution modality and spatial arrangement. The electrical and vibratory interfaces (ELE4 and VIB4) yielded similar RR in both the SD and PD experiments. These results differ from those reported by Witteveen et al. [31] that showed improved outcomes when using vibrotactile as compared to electrotactile stimuli. However, in their work the authors used traditional electrodes with a single, distally located common electrode (instead of concentric electrodes as in the present study). This might have decreased the focus of the sensations elicited and impaired the ability of the subjects to localize the active channel.

The similar RR achieved with VIB4 and ELE4 experiments could be due to the relatively large inter-element distance. At smaller distances closer to the spatial discrimination threshold, the well localized sensations produced by the concentric electrodes could show a pronounced difference on the results, in favor of the electrotactile interface. However, it was not possible to place the concentric electrodes closer than 4 cm due to their size. Hence an electrotactile equivalent to VIB2 could not be assessed. The lower distance between vibrotactile devices of VIB2 compared to VIB4 (4 cm vs. 2 cm) diminished the user's RR in both SD and PD experiments; this is likely to be explained by the fact that the distance used in VIB2 was very close to the spatial vibration discrimination threshold on the forearm (i.e. 2-3 cm) [33], [34].

In the SD experiments a significant difference in RR was identified across the different sites of stimulation with VIB2: the stimulation sites on the lateral part of the forearm were more easily discriminated than the medial ones. This difference is likely to be due to the lower sensibility of the medial side of the forearm vs. the lateral side [35].

Some subjects reported that despite the lowest stimulation levels, they still experienced diffused and/or referred sensations with electrical stimulation at some channels. In particular the electrodes that were located on the inner side and close to the medial axis of the forearm, often elicited sensations that were spread (referred) along the forearm and hand. This kind of sensations in fact assisted in recognizing the stimulation of that specific channel in SD experiments but, since the sensation masked the stimulation of the neighboring channels, it made it harder to discriminate the neighboring patterns during PD experiments. As regards to vibrotactile stimulation in PD experiment, the vibrations from the different channels summed together; subjects reported that since the sensation elicited was qualitatively similar for all stimulation sites, they could also use the level of general intensity felt in addition to the spatial location of the active vibrators, as an aid in discriminating the patterns. The current experiment was performed using minimal intensities. However, since the

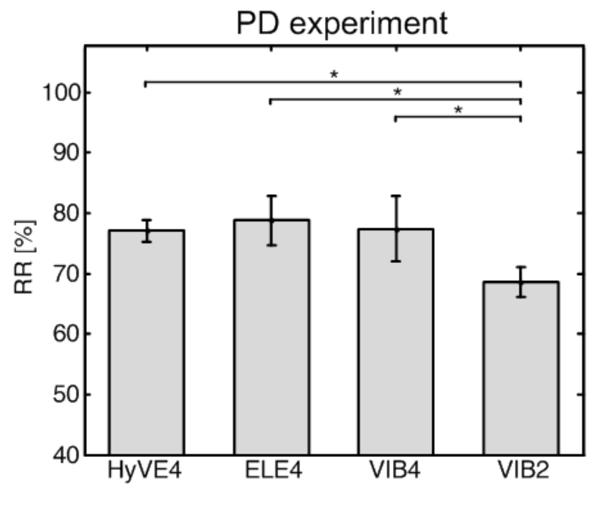

Fig. 7. Overall recognition rates (mean ± standard errors) obtained in the PD experiment (asterisks indicate $p<0.05$).

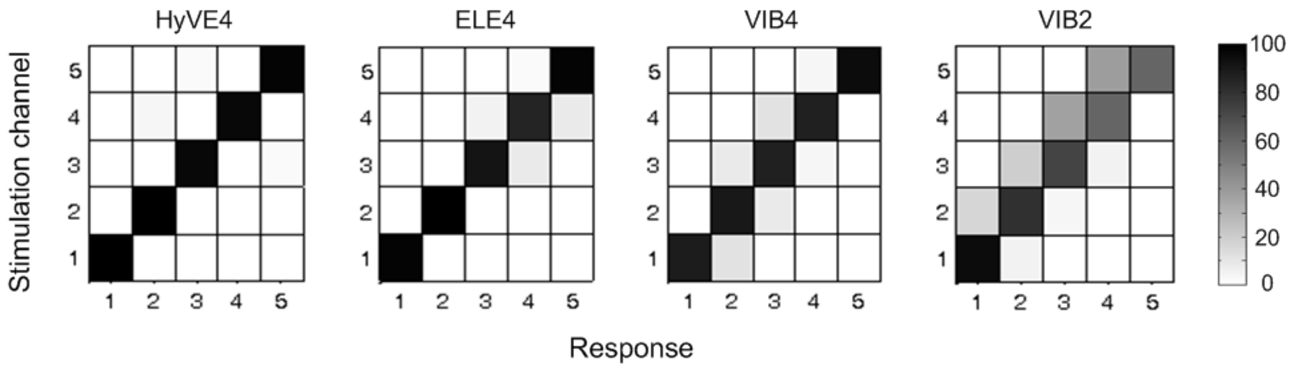

Fig. 8. Confusion matrices of the recognition rate obtained in the pattern discrimination experiment.

aforementioned phenomena influence the discrimination of the stimuli, further studies should be made to evaluate the effect of stimulus intensity on the the recognition of electro and vibrotactile spatial patterns.The RR in the reinforced learning phase was not statistically different from the RR in the validation phases in any of the cases, except for HyVE4 in the SD experiment. This means that the training failed to improve the performance in these cases. The reasons for this could be however very different. The task could have been easy for the subjects resulting in a high performance from the beginning, so that the training was not truly needed (e.g., ELE4 and VIB4 in SD experiment). On the other hand, in the conditions with the lower success rates (e.g., PD experiments, SD with VIB2) the task could have been too difficult for the provided (short) training to improve the performance significantly. The training had an effect only in the case of HyVE4 configuration and SD experiment. This could be due to a higher initial difficulty of the participants to identify a single active channel not only by using spatial but also stimulation modality information. An important future step could be to assess through a longitudinal study how the performance depends on the amount of training the subjects receive.

SD and PD experiments have been used in this study to evaluate the ability of the human subject to receive discrete information (i.e., single or multiple finger contact) delivered in the form of a multi-channel spatial tactile pattern. The channels were arranged circumferentially around the forearm and assigned to the fingers so that the channels and the respective fingers were more or less spatially congruent. We assumed that this configuration will be used in the future with the real prosthesis since the correspondence between the channels and the fingers is in this case very intuitive (e.g., compared to a multi-channel array in which the channels would be placed medially and along the forearm [31]).

In the future tests, we will evaluate the possibility of transferring to the user continuous information capturing a dynamically changing state of the prosthetic hand. This can be a signal corresponding to the current aperture or grasping force. In our previous work [27], we have demonstrated how a single HyVE can be used to convey information through intensity modulation. Therefore, multiple HyVE units can be used to implement a high fidelity but compact multi-modality interface for spatial and intensity coding. Many mappings from sensor data to stimulation patterns are possible, and this will depend on the sensory system embedded into the prosthetic hand and feedback design goals (e.g., a tradeoff between the size and fidelity of the interface). For example, aperture and force could be transmitted using an array of HyVE stimulators; the information could be conveyed through the number/position of active devices (spatial coding) and each feedback signal could be coupled for a specific stimulation modality (e.g., vibro for force, electro for aperture). The resolution of this coding would be given by the number of stimulators. Alternatively, each HyVE could transmit the angle (electro) and force (vibro) of an individual finger (5 HyVEs in total), allowing thereby a complete characterization of the state of a dexterous prosthetic hand. Finally, one modality could be used for finger position/force and the other to indicate the occurrence of a slip. Of course, the performance of HyVE in these interesting and relevant practical applications has yet to be tested experimentally.

A multi-channel and multi-modal interface with a small form factor such as the HyVE could be useful for many portable systems providing haptic feedback. In general, such a system could be employed in all applications in which there is the need to provide sensor data to the subject using a multi-channel tactile display. Possible candidates are rehabilitation systems, navigation guidance for blind people, video game controllers, telemanipulation systems, virtual reality environments etc. In particular, our device provides also an excellent platform to investigate and implement new solutions within the field of cognitive infocommunications (CogInfoCom). This field centers on the analysis of existing and synthesis of new forms of communication between humans and electronic devices, especially when the artificial systems also have some cognitive abilities (intra and inter-cognitive communication) [36], [37]. This in fact becomes an increasingly relevant context in the field of rehabilitation engineering as the assistive and prosthetic systems become more and more intelligent and capable of autonomous processing and decision making [38], [22]. The multi-channel HyVE can be used to map any sensor data of interest (contact, forces, angles etc.) to multiple tactile sensory channels, allowing thereby the exploration of strategies for sensor and representation bridging and sharing (as defined in CogInfoCom [36]). As a multi-modal and multi-channel device, the HyVE could be useful to devise and compare information coding schemes and evaluate the ability of a human subject to integrate the information transmitted through different tactile sensory channels and stimulation modalities. All in all, there are many promising hybrid combinations yet to be explored and the initial findings in this paper could stimulate the further research into different fields.

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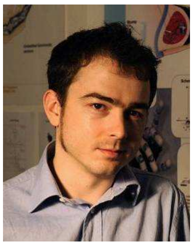

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