Application of Radio-Finger Augmented Devices to Cognitive Neural remapping

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***Abstract*—Finger-Augmented Devices having wireless connectivity based on battery-less backscattering (RFID-FAD) are useful assistive tools for subjects suffering from *Hypoesthesia*. This work presents an optimized R-FAD system consisting of a conformal sensor-tag sized for the fingertip and a wrist-mounted module (antenna+reader) that powers the on-chip finger sensor, collect the data transmitted back and convert them into acoustic feedback. Beyond the use as a disability aid, the R-FAD system is here applied, for the first time, in the context of cognitive neuroscience, to investigate if the loss of physical perception of the warmth could affect also the abstract/mental representation of the temperature, as claimed by the *grounded theories*. Preliminary tests, involving both control healthy subjects and a deafferented patient, corroborate this theory and, above all, suggest that the training with the R-FAD system, providing a 'transduced' thermal sensitivity, may play a role in the cognitive re-mapping of the thermal perception.**

***Index Terms*—Radiofrequency Identification, Epidermal Electronics, Wearable sensors, FAD, Wearable sensors, UHF antennas.**

I. Introduction

Moving the hand away immediately after touching an hot object - before even feeling the pain - is a unlearned, involuntary (automatic) response - known as *withdrawal reflex* - that we continuously experience in our daily life. People suffering from *Hypoesthesia* - a common side effect of various pathological conditions (e.g. peripheral neuropathy, diabetes, chemotherapy...) associated to a reduced sense of touch and a partial/total loss of sensitivity to sensory stimuli - lack of such innate behavior that protects the body from harmful events. Accordingly, they are continuously exposed to the risk of severe burns and other crippling deficits, with a serious negative impact on the quality of life.

Beyond the physical impairments of these patients, neuroscientists have been recently interested in investigating also the impact of such loss on the cognitive/psychological sphere. Indeed, according to the *grounded theories* of cognition [1], the physical and the abstract representation of the same concept, including temperature, are conceived as intimately related. Experiencing physical warmth or coldness can bias first-impressions of personality and attitudes towards others in the direction of the sensory prime [2]. For example, briefly holding a hot coffee cup or sitting in a warm room induces individuals to feel interpersonally closer to a target person and describe him as endowed with a significantly 'warmer' personality if compared to when holding a cup of iced coffee or sitting in a colder room [3]. Interestingly, the interaction is bidirectional: experiences of social coldness, as in social exclusion, cause participants to perceive room temperature as colder than do experiences of acceptance and inclusion [4]. This link can be explained in neural terms, as the insular cortex is implicated in processing both the physical and affective dimensions of thermal information [5].

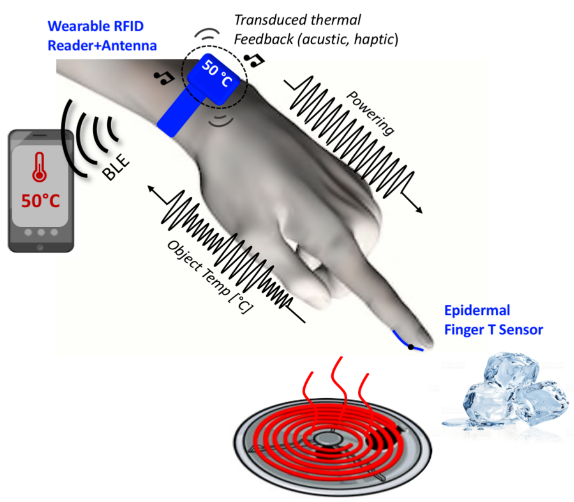

Figure 1. UHF R-FAD system for recovering thermal feeling, comprising a conformal passive finger-tag and a wrist interrogating module (antenna+reader).

Driven by the enormous progresses in *Flexible/Stretchable Electronics* [6], novel assistive solutions based on Finger Augmented Device (FADs) have been proposed [7] to provide impaired subjects with a comfortable technological recovering of their physical limitations (or even expanding their senses beyond the natural ones). Recently, the authors have demonstrated the feasibility of a RadioFrequency Identification-based FAD system (hereafter R-FAD) [9], [10] which merges together the advanced electronics interfaces typical of FADs tools with the wireless communication architectures based on passive backscattering (UHF RFID). The R-FAD system (Fig.1) comprises an epidermal-like battery-less transponder (tag) shaped for the fingertip that, when wirelessly sourced by a wrist-mounted antenna, powers up the IC circuitry, measures the temperature of the touched surface and transmit the data back to the reader for processing.

Starting from the previous works, this paper presents an original application of an optimized R-FAD device in the field of Neuroscience. The reported experimental study, involving both healthy volunteers and a patient suffering from a serious thermal loss over a large part of the body, aims at investigating if the deficiencies in thermal sensory function may impact on the associated concepts and/or behaviors, as claimed by grounded theories [1] and, if so, the possible role of traning with the R-FAD assistive device in stimulating the recovering of emotional feeling of temperature (cognitive remapping).

II. The R-FAD System

The R-FAD system shown in Fig. 1 includes four main components: *i)* a conformal tag stuck over the finger having temperature sensing capability; *ii)* a wearable interrogation antenna integrable within a wristband and connected to a *iii)* battery-powered portable reader and *iv)* a processing unit, running locally on the wrist module or on the smartphone connected via BLE, which performs the device-level filtering of the measured data and the conversion into a acoustic/visual/haptic feedback that can be naturally interpreted from the wearers.

1) The Fingertip Tag: is conceived to perfectly fit the area of a fingertip (12x20mm). The layout consists of a planar loop fed by the IC and inductively coupled to a wired meandered dipole with smoothed corners (Fig. 2). An insulating 1mm-thick bio-silicone membrane (ε_r =2.2, σ=5e-3 S/m) is interposed between the central loop, where the highest value currents are expected, and the epidermis to reduce the losses and, accordingly, improve the efficiency of the tag. The connected IC (Magnus-S3, P_{chip} = -16.6 dBm) includes a on-chip digital temperature sensor (range -40 °C < T < 85 °C, accuracy ΔT = ±0.5°C) and a self-tuning mechanism, i.e. it automatically adjusts its internal multi-state capacitance to compensate for the impendence mismatching caused by changes of the boundary conditions. (e.g. when the finger touched different objects).

2) The Wrist-mounted patch antenna: is a shorted patch (derived from [10]) having a miniaturization slot on the upper metallization and a short-circuit edge with variable-length for frequency tuning. The substrates is a low-permittivity foam (3mm-thick forex, ε_r=1.55, σ=6e-4 S/m) with moderate flexibility. The ground plane ensures a partial electromagnetic decoupling from the arm as well as shielding from the electronics of the reader to be mounted below metal layer for a compact layout.

The overall system in Fig.2 was numerically simulated on a reference homogeneous hand phantom (ε_r = 30, σ= 0.62 S/m) by Finite-difference Time domain solver (CST Microwave Studio). As the wrist-to-finger channel takes place in the radiative near-field, with strong interactions (scattering, reflections, power absorption) produced by the human body, the two-ports network formulation is adopted [10]. Accordingly, the link performance is quantified through the *Transducer Power Gain* (G_T):

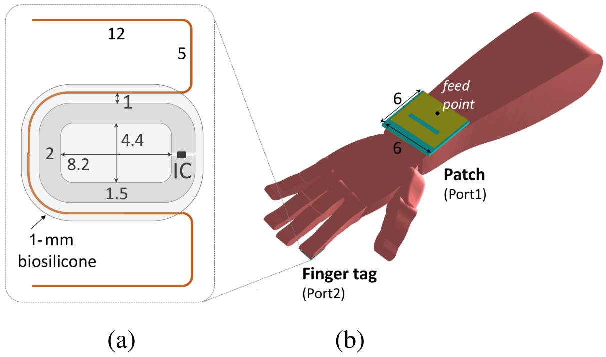

Figure 2. Layout of the conformal tag to be placed on the finger and 3D cad model of the entire R-FAD system used for the numerical simulations.

$$G_T = \frac{P_{R\to T}}{P_{av,R}} \tag{1}$$

where $P_{R\to T}$ is the power delivered by the reader to the chip, in the specific impedance matching condition, and $P_{av,R}$ the available power emitted by the reader generator. This indicator is useful to compare simulation with measurements, as shown in the next section.

A. Prototypes and characterization

The finger tag was prototyped by profiling a coated copper microwire (80 µm-radius) around an aluminum-etched loop (PET inlay) and deposited over an adhesive medical-grade polyurethane film (Fixomull, 20μm thickness). This manufacturing is suitable for mass-production targeting a very low price (<1$ over the large scale) that is compatible with a disposable use of the finger . The fabricated conformal device was attached on the finger by means of the same polyurethane film used as substrate and resulted totally imperceptible for the wearer, whose natural hand gestures and hand-free interactions with surroundings objects were absolutely preserved (Fig.3).

Figure 3. Prototype of the flexible finger tag attached on the fingertip by means of a breathable polyurethane film.

The entire R-FAD was characterized as a whole in terms of G_T, that was experimentally derived from the measurement of the *turn-on power* of the tag (P_{to}), i.e. by increasing the reader's power until the chip activates ($G_{Tmeas} = \frac{P_{chip}}{P_{to}}$). Fig. 4 shows that the measurements over three different

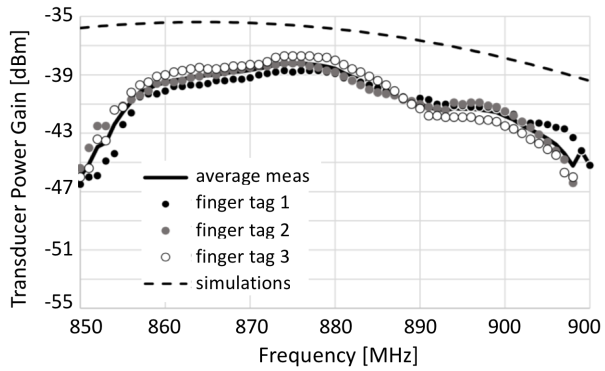

Figure 4. Measured Transducer Power Gain of the R-FAD system for three different prototypes of the finger tag worn by a volunteer (hand size: length=20 cm, width=9 cm). Comparison with simulated data.

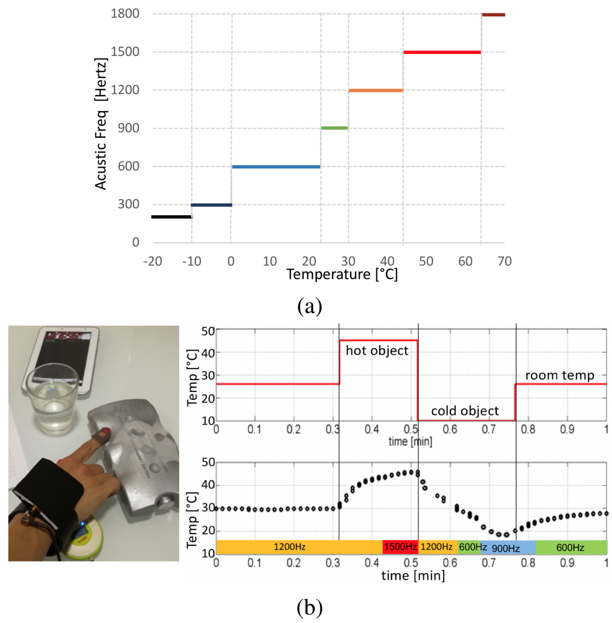

Figure 5. (a) Conversion of the temperature into a frequency-modulated acoustic signal. (b) Temperature measured when the user's finger touches objects at different temperatures. The visual/audio feedback provided by the app in the inset.

prototypes worn by a volunteer are very reproducible (overall σ=±0. 6dB) and in good agreement with numerical simulation (difference less than 3 dB in the matched UHF band). At the peak value ($\overline{G}_{T,peak}$= -38 dB within 870-880 MHz), the input power required to wake up the sensor is around 22 dBm. This value can be provided by commercially available watch/keyfob-like portable readers that generally emit from 23 to 27 dBm.

B. *Example: R-FAD for measuring the objects' temperature*

The R-FAD gives to the wearer the feedback about temperature of the touched objects by means of acoustic and visual signals generated by a custom mobile app. Starting from the medical literature regarding the human cold/warmth perception [11], the IC temperature range was discretized in seven intervals corresponding to as many sounds whose frequency was proportional to the temperature level (Fig.5.a). An example of a temperature profile measured when the users touches hot and cold object is shown in Fig. 5.b, together with the feedback generated by the app. Even tough the temperature measured by the fingertip sensor differs from the absolute one due the thermal inertia of the IC, the combined processing of both sensor and power signals permits to estimated the real temperature of the object, even in the case of short touching (less than 0.5sec) (see [12])

III. Cognitive Tests

The developed R-FAD system was employed in a neuroscience study having the two-fold purpose of *i)* assessing if the chronic loss of peripheral sensation may loosen the association between the temperature concept and its sensory proxy and, in positive case, *ii)* evaluating if actions aimed at restoring the sensory loss, by means of R-FAD device, may trigger possible 'transduced' recovery of the cognitive thermal feeling.

Twenty-one subjects were enrolled for the study: 20 neurologically intact controls (mean age 30±9 years) and one patient (Female, 45y) suffering since 2010 from complete loss of thermal sensation from both upper limbs, below the elbow, and over a large part of the trunk caused by a chemioterapic treatment. The participants signed a informed consent, received a cover story describing the administered tests but they were not fully aware about the final purpose of the study to avoid any biased behavior. The experimental protocol included a chronometric task testing the implicit association between the cognitive and physical concept of temperature. The deafferented patient was tested twice: i) before using the R-FAD (baseline measure) and ii) a few days after ending the training period with the R-FAD. Neurologically intact individuals were tested once and served as normative controls.

A. *Training Session (patient only)*

The patient performed the training at home by autonomously using the device (approx. every day) in a series of 20-min sessions over 15 consecutive days. She wore the R-FAD with the sensor on the index of the dominant limb (Fig. 6). She was asked to randomly touch multiple times three objects at different temperature (a cup filled with hot water, an ice pack, a stress-ball kept at room temperature) and to provide estimations of the 'perceived' temperature from the played sound (the acoustic sensory level was perfectly intact in the patient). The natural decay of the initial temperature of the hot and cold stimulus across time ensured an evaluation of an ecological range of object temperatures (room temperature of the stress-ball would act as control). The patient was invited to provide the estimations while keeping her eyes closed, in order to minimize influence from other senses. At the end of the training the patient demonstrated a remarkable accuracy in estimating the temperature of the objects (6).

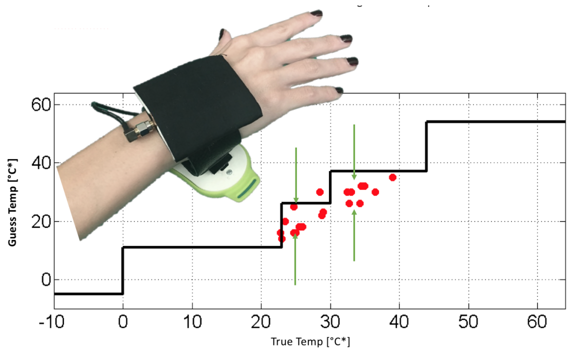

Figure 6. Objects' temperature vs temperature estimated by the patient through the R-FAD.

B. Test session: Stroop-like task

In a classical Stroop-like task, participants must name – as quickly as possible – the color of ink in which *color-names* are printed (e.g. the word 'yellow' printed in the color 'blue'). Automatic processing of *color-name* is indeed known to produce an interfering effect, which significantly delays the ink-naming task [13]. A comparable effect occurs also for words that are not themselves color names – but implicate color in their meaning (*color words*, e.g. grass/green, fire/red, lemon/yellow, etc.), confirming that sensory attributes of an item are embedded in the verbal concept. Theoretically, a larger interference effect is expected in controls. If concepts are indeed experience-dependent representations, we hypothesized that chronic loss of peripheral sensation may progressively loosen the association between a concept and its sensory proxy, and – consequently, reduce the interfering effects that word reading causes on the ink-color response. In the same way, replacement for the sensory loss through the R-FAD should eventually restore the interfering effect.

The achieved results, evaluated in terms of response time [RT] are shown in Fig. 7. At baseline, i.e. before the R-FAD use, the deafferented participant showed an interfering effect for *color-names* but not for *color-words*. In fact for color-words response times were slower in 66.4% of controls compared to the deafferented participant, suggesting that the incongruence between color of the ink (e.g. 'green') and color evoked by the verbal concept (e.g. 'fire') played a minor interfering effect in case of sensory loss. Namely, the interfering effect appeared to be somewhat smothered in the deafferented participant, possibly suggesting a reduced contribution of sensory properties in concept processing/manipulation. Interestingly, after R-FAD use, the responses of the deafferented participant for color-words resemble the pattern displayed by neurologically intact individuals.

IV. Conclusions

The R-FAD system including epidermal wireless sensors revealed also a useful tool for supporting cognitive

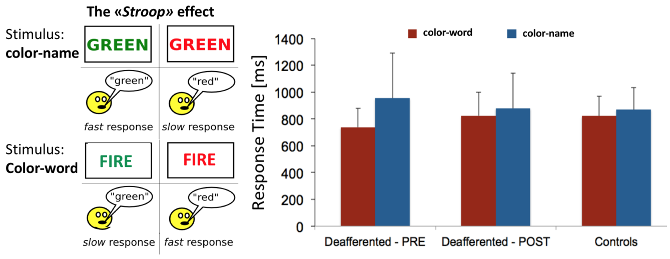

Figure 7. Response time [RT] acquired for the Stroop-like-task.

studies. The presented experiments, yet very preliminary, confirm that the loss of thermal sensitivity could actually compromise the implicit association between sensory and conceptual/emotional dimensions of warmth/coldness. Albeit caution is imposed by the single case description, the early results suggest that, being experience-dependent, the abstract mental concept of temperature could be re-mapped by replacement strategies like the R-FAD aided system. Further experimental results will be show during the conference.

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