Two-point vibrotactile discrimination related to parameters of pulse burst stimulus

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Abstract—*Tactile spatial resolution is an important factor in the design of vibrotactile arrays. The two-point discrimination distance is used as a measure of tactile spatial resolution. An experimental study is presented showing the effect of pulse burst stimulus parameters, pulse repetition period and duty cycle on two-point vibrotactile spatial discrimination. An array of piezoceramic vibrators is used to measure two-point spatial discrimination on the index finger. In a group of 14 subjects, the average two-point discrimination distance for a pulse repetition period of 1/25 s is 2.1 mm (SD = 1.0), whereas for 1/500 s it is 5.1 mm (SD = 0.9). Differences in discrimination distances are statistically significant according to the ANOVA analysis ($p < 0.001$). Results show that the two-point discrimination distance is better for longer pulse repetition periods. Therefore the pulse repetition period in an excitatory waveform composed of bursts of pulses is important for tactile resolution. No statistically significant differences in discrimination distances are found between bursts of pulses of 50% duty cycle and those of lower duty cycle. The latter result indicates that, by choosing low-duty cycle waveforms for vibrotactile stimulation, the power can be reduced with no loss in two-point discrimination capacity.*

Keywords—*Two-point vibrotactile discrimination, Vibrotactile resolution, Vibrotactile excitation, Tactile excitation, Tactile parameter optimisation*

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1 Introduction

1.1 *General background*

THE POSSIBILITY of transferring information through tactile stimulation to visually handicapped individuals was demonstrated almost three decades ago (BACH-Y-RITA *et al.*, 1969). Nevertheless, the bulk, weight, inefficiency and high cost of the hardware involved remain an obstacle to building portable devices for the blind community (BRABYN, 1985; KACZMAREK *et al.*, 1991). Many other applications of vibrotactile displays are of interest, including virtual reality (CHU *et al.*, 1997; DIONISIO *et al.*, 1997; IKEY *et al.*, 1997).

The tactile sense responds to frequencies in the range 25–700 Hz, with maximum sensitivity—in terms of displacement amplitude—at around 250 Hz for sinusoidal excitation (VERRILLO *et al.*, 1969; JOHNSON and PHILLIPS, 1981; LAMORE and KEEMINK, 1988; SUMMERS *et al.*, 1994; GESCHEIDER, 1996). Mechanical stimulation of the skin evokes a neural response that can be subdivided into responses by the four mechanoreceptor populations innervating primate glabrous skin: the slowly adapting SAI and SAII, rapidly adapting (RA) and Pacinian afferents (TALBOT *et al.*, 1968; PHILLIPS and JOHNSON, 1981; JOHNSON and HSIAO, 1992).

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Sensitivity thresholds also depend on the size of the contactor and on the presence of a rigid surround around the contactor (LAMORE and KEEMINK, 1988; CHOLEWIAK and WOLLOWITZ, 1992). As psychophysical experiments show maximum sensitivity to sinusoidal excitation in the 200–300-Hz region, from the power requirement point of view, it would be advantageous to operate a vibrotactile system in this range (ROGERS, 1970). Other studies indicate that slowly adapting receptors may be superior in terms of their ability to localise stimuli (TALBOT *et al.*, 1968).

1.2 *Power considerations*

Power consumption is an important factor in the design of practical body-worn devices for the sensory handicapped (NUNZIATA *et al.*, 1989; CHOLEWIAK and WOLLOWITZ, 1992; SUMMERS *et al.*, 1994). It is possible to reduce system power requirements and hardware components by finding an appropriate excitatory waveform that suits the tactile system physiology. Several studies in vibrotactile stimulation have been published, partially achieving this goal (BRABYN, 1985; KACZMAREK *et al.*, 1991; NUNZIATA *et al.*, 1989; CHOLEWIAK and WOLLOWITZ, 1992; PEREZ and MUÑOZ, 1995).

For a driving waveform composed of a train of rectangular pulses followed by a recovery time, as shown in Fig. 1, the most significant parameters are: pulse width (PW), pulse repetition period (PRP), number of pulses per burst (NPB), and recovery time (RT). In this waveform, the stimulatory time $ST = NPB \times PRP$. The recovery time prevents physiological tactile adaptation to the stimulation. It was shown that RT also

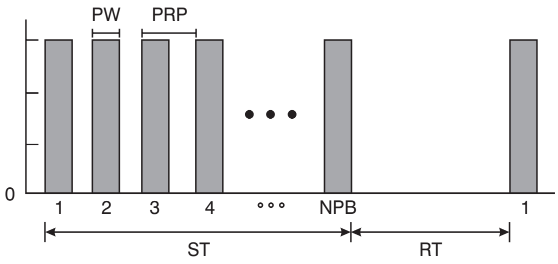

Fig. 1 *Driving waveform composed of burst of rectangular pulses followed by recovery time. Parameters of waveform are pulse width (PW), pulse repetition period (PRP), number of pulses per burst (NPB), stimulatory period (ST) and recovery time (RT)*

reduces the power requirements, with no reduction in sensitivity (NUNZIATA *et al.*, 1989). Therefore a given stimulus can consist of multiple bursts of pulses, according to each subject's requirements.

The duty cycle (DCY, %) of the waveform is given by $DCY = 100\,PW/PRP$. It has been shown that the power delivered to the system can be reduced by using an excitatory rectangular pulse waveform with low DCY, relative to 50%, while maintaining similar levels of sensitivity (NUNZIATA *et al.*, 1989; PEREZ and WEED, 1991).

Besides the possibility of power optimisation, there are other reasons to prefer the excitatory waveform given in Fig. 1 over analogue waveforms. Pulses are simple to generate with digital components, and the off periods between pulses permit multiplexation of several signals into one physical channel for hardware reduction. In PEREZ and MUÑOZ (1995), the PW was optimised for each PRP so as to maximise the ratio between the power delivered to the frequency region of maximum tactile sensitivity (25–700 Hz) and the total power delivered by the waveform. Optimum pulse widths were in the range 0.7–1.2 ms. All previously cited studies have focused on the optimisation of the power delivered to the frequency region of maximum tactile sensitivity, but they have not considered the possible spatial tuning of the tactile sense with respect to the parameters of the excitatory waveform.

1.3 *Spatial discrimination*

In clinical practice, a two-point discrimination distance for a static stimulus is routinely used as a measure of tactile resolution (VON PRINCE and BUTLER, 1967; WERNER and OMER, 1970; JONES, 1989; JIMENEZ *et al.*, 1993). The classical two-point limen test determines the smallest two-point separation at which the subject feels two points instead of one. Instruments such as callipers and monofilaments are used for this purpose. Other instruments have been developed to automate this test (HORCH *et al.*, 1992; LAMOTTE *et al.*, 1983). However, the automated tests have not been used to determine dependency of the two-point discrimination distance and the tactile stimulus parameters.

Several studies have considered dynamic vibrotactile stimuli for sinusoidal excitation. Subjects reported a deeper, more diffuse vibrating sensation at sinusoidal frequencies above 40 Hz. Thus, for a person using a tactile display, the use of low stimulator frequencies was suggested (20–40 Hz) to improve the person's ability to perceive spatial information (ROGERS, 1970). Nevertheless, subjects showed improvement in letter recognition for high stimulator frequencies. It was also found that the ability of the subject to discriminate differences in intensity was significantly better at 250 Hz than at 10 Hz when two stimulators placed on the fingertip were 2 mm instead of 6 mm apart. No differences were found for distances between stimulators in the range 6–10 mm. It was inferred that the spatial resolving power of the high-frequency system was superior to that of the low-frequency system (ROGERS, 1970). There is evidence indicating that the spatial acuity of the RA system may be three times poorer than that of the SAI system, and therefore form perception may be dominated by the SAI system (JOHNSON and HSIAO, 1992). Tactual letter recognition appears to be directly related to the properties of the SAI system (JOHNSON and HSIAO, 1992). The RA system appears to be responsible for the detection of flutter, slip and motion across the skin surface (BLAKE *et al.*, 1997).

A different test from the classical two-point limen test was developed to measure tactile resolution (JOHNSON and PHILLIPS, 1981). This test measured the ability of subjects to discriminate between single- and double-point stimuli (each point of 0.5 mm diameter). The method considered a subject who had to identify a stimulus sequence of two points followed by one point, or one point followed by two points. The results showed that subjects were able to distinguish between both sequences of stimuli, even though the gap separating the two points was null. The results also showed that the effect of force (10, 30 and 80 g) on the discrimination distance was not significant. It was proposed that the neural mechanisms could have discriminated between one and two points on the basis of the number of active fibres and total number of action potentials, because of the difference in overall dimensions and contact area of the contactors (JOHNSON and PHILLIPS, 1981).

The capacity for discriminating vibratory stimuli on the sole of the foot was tested using a 200-Hz sinusoidal impulse frequency (KOWALZIK, 1996). The discrimination threshold was defined as the shortest distance at which two vibrations can be differentiated at repeated trials. Discrimination distances decreased along the longitudinal axis of the foot from distal to proximal parts and was about 15 mm at the big toe and 34 mm at the heel.

Another study measured two-point discrimination thresholds on three different sites, including the index finger, in a group of 47 healthy children between 6 and 13 years of age (MENIER *et al.*, 1996). Threshold values were similar to those of adults. Discrimination distances were also measured for dynamic conditions where the two points were sliding in a transverse direction. It was found that discrimination distances were lower for dynamic tests than for static tests and that there were no significant differences between passive and active movements on discrimination. Active movement meant that the child actively placed the index finger on the instrument to measure the two-point discrimination distance (MENIER *et al.*, 1996).

Several papers have investigated the tactile recognition of patterns but were not directed towards the waveform parameters (CRAIG, 1983; CRAIG and QUIAN, 1997). Discrimination of vibrotactile frequencies in a delayed pair comparison was investigated in SINCLAIR and BURTON (1996). The performance decreased as a function of the length of delay. A device was developed to measure tactile sensitivity using active touch, rather than passive tactile stimulus (RADWIN *et al.*, 1993). In this case, instead of detecting two points or a single point of pressure, a tiny gap is detected in a smooth surface. Index-finger tactile sensitivity thresholds for 15 individuals had a mean value of 0.17 mm, which represents almost an order of magnitude less than the static sensory test (RADWIN *et al.*, 1993).

Other efforts include a device to measure tactile spatiotemporal sensitivity using an array of 88 piezoelectric plates (VANDOREN *et al.*, 1987). Detection thresholds were measured for five temporal frequencies and five spatial wavelengths, thus generating a coarse sampled frequency response. The spatio-temporal stimuli involved only sinusoids, with the objective of performing linear analysis (VANDOREN *et al.*, 1987). In PEREZ *et al.* (1998), results were presented on the two-point spatial discrimination distance as a function of PRP and PW using tangential stimulation to the skin. Results showed that the two-point discrimination distance was better for longer than for shorter PRPs.

1.4 *Present study*

In the present study, an experimental investigation into the effect of PRP and PW on two-point vibrotactile spatial discrimination is presented. The excitation is perpendicular to the skin, as in most vibrotactile applications. Three different cases were considered as a function of PRP. The first case considered 50% DCY and fixed NPB (variable ST). The second case consisted of lower DCY, with fixed PW of 0.7 ms and fixed NPB (variable ST). The third case consisted of low DCY, with fixed PW of 0.7 ms and fixed ST (variable NPB). The 0.7 ms PW was selected from power optimisation parameters (PEREZ, 1991; PEREZ and WEED, 1991; PEREZ and MUÑOZ, 1995). The aim of this work is to contribute to the design of an optimised waveform for small power consumption in vibrotactile stimulation, to be used for information transfer in any device for the sensory handicapped.

2 Methods

Two-point discrimination was measured using an array of 16 piezoelectric vibrators mounted as illustrated in the schematic diagram of Fig. 2. Each vibrator was a rectangular piezoceramic bender with dimensions 23.0 mm length, 3 mm width and 0.5 mm thickness, as shown in Fig. 3. Piezoceramic vibrators are, in general, more power efficient than electromagnetic transducers (CHOLEWIAK and WOLLOWITZ, 1992). The vibrators were mounted in a cantilever manner in a plastic base. The 16 vibrators were positioned as shown on Fig. 4, so that two-point stimulation distances from 1 to 15 mm, in steps of 1 mm, could be achieved between two of them.

The index finger was selected for the experiments because of its high spatial resolution and because it is the principal area used for tactile exploration (WEINSTEIN, 1968; VANDOREN *et al.*, 1987; COREN and WARD, 1989; SUMMERS *et al.*, 1994). Furthermore, the index finger has been used as interface in many assistive devices for tactile information transfer (CHOLEWIAK and CRAIG, 1984).

The experiments were performed on the distal pad of the index finger, using a circular contactor of 0.56 mm diameter with no surround. The hand rested on an aluminium cover over the array of vibrators, as shown in Fig. 4. The array of vibrators contacted the skin through a 5 mm × 10 mm rectangular hole filled with an acrylic plate with 16 circular perforations, of 0.75 mm diameter,

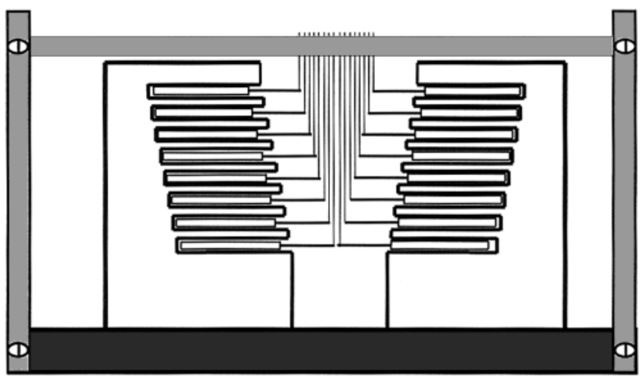

Fig. 2 *Schematic diagram showing array of 16 piezoelectric vibrators mounted horizontally in cantilever manner with vertical contactor to touch skin*

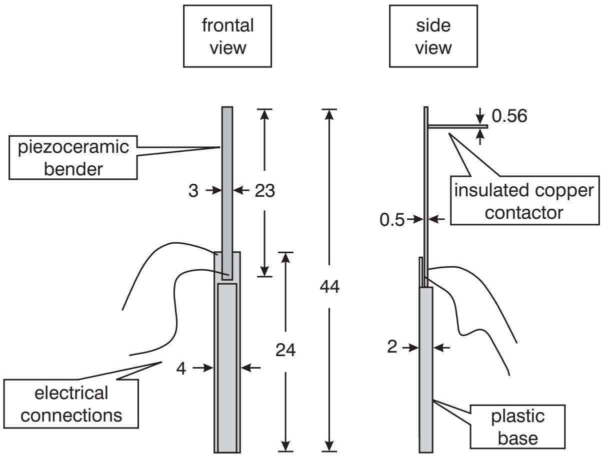

Fig. 3 *Detailed schematic diagram of connections and dimensions, in mm, of each piezoelectric vibrator. Frontal and side views are shown*

to allow the contactors to touch the skin. This arrangement is similar to several other experimental tactile displays, including devices such as the Optacon (MUIJSER, 1994). The height of the metal plate relative to the vibrator contactors was adjusted to maintain a constant load close to 0.04 N on the vibrators. This load was measured using a photonic sensor*. Similar arrangements have been used in experiments in SUMMERS *et al.* (1994) and RADWIN *et al.* (1993).

Two-point vibrotactile stimulation was produced by exciting two vibrators at the same time with the waveform shown in Fig. 1. The stimulus amplitude was maintained around 20 dB above the absolute sensation threshold to ensure that both contact points elicited tactile sensation at all PRP. The frequency response had been measured previously on a different population with the same set of vibrators (PEREZ *et al.*, 1998). The amplitudes were preprogrammed on a system based on a microcontroller, and therefore the time involved in changing from one type of stimulus to another was not significant.

The experiments considered three different combination of parameters, while the PRP varied for 1/25, 1/50, 1/100, 1/150, 1/250, 1/350 and 1/500 s. Case 1 considered 50% DCY, i.e. $PW = PRP/2$. Case 2 considered a low DCY with a fixed PW of 0.7 ms (NUNZIATA *et al.*, 1989; PEREZ and WEED, 1991;

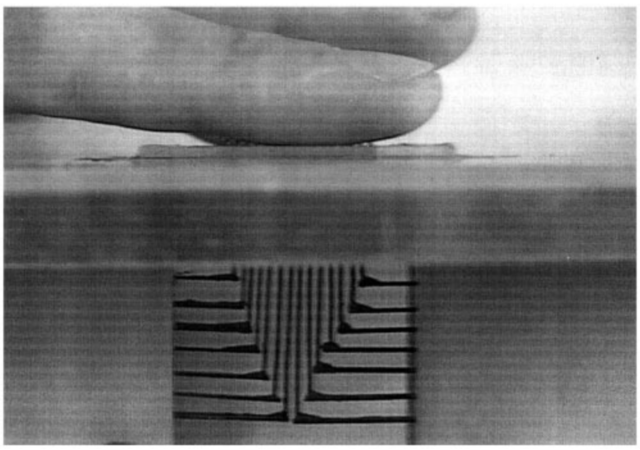

Fig. 4 *Array of 16 piezoelectric vibrators and how contactors touch index finger. Acrylic rectangle on top contains 16 circular holes to guide contactors, maintaining 1 mm distance between neighbours*

*National Instruments Inc.

PEREZ and MUÑOZ, 1995), and case 3 considered low DCY with a fixed PW of 0.7 ms and a fixed ST of 200 ms for all PRP. In cases 1 and 2, the stimulatory period lasted within the range 40–800 ms, depending on the PRP as in SUMMERS *et al.* (1994). In case 2, the fixed PW implies a different DCY for each PRP, and, in case 3 the fixed ST implies a different NPB for each PRP. Table 1 shows a summary of the waveform parameter values for cases 1–3. For each measurement in the three cases the PRP, PW and ST were fixed according to the values in Table 1. The method of the limits (COREN and WARD, 1989) was used to determine the two-point discrimination distance. Starting from the minimum distance of 1 mm, the distance between the two points was increased until discrimination was achieved. Then the distance was decreased, until the subject could not discriminate the two separate points of stimulation. For each measurement, the subject was asked to identify one or two points of excitation; the minimum distance was registered. The discrimination distance was determined as the average of the 'up' and 'down' thresholds.

All subjects were trained for 1 h to discrimnate one or two points of excitation at different PRPs one day prior to the test. Fourteen young healthy university students aged 24–31 years, were tested for the two-point discrimination exam for cases 1 and 2. A complete test sequence for all PRPs was measured for each subject. The experiment was also repeated 14 times on two different subjects to assess individual data dispersion. As ST = 20 PRP, it was necessary to determine whether the dependence of the two-point discrimination was due to PRP or ST. As ST was variable in cases 1 and 2, case 3 was included to compare results for fixed ST. A group of eight subjects were tested for case 3. In previous work on tangential stimulation of the index finger, it was found that the discrimination distance had the same dependence as a function of PRP for fixed or variable ST (PEREZ *et al.*, 1998).

Statistical analysis of the experimental data was performed to determine the significance of the differences in results for different test conditions. A two-factor ANOVA analysis (ROSNER, 1986) was applied to the two-point discrimination distances for all PRPs and cases 1–3.

Table 1 Waveform parameter values for cases 1–3. Parameters of waveform are pulse repetition period (PRP), pulse width (PW), stimulatory period (ST), number of pulses per burst (NPB) and recovery time (RT)

Cases	*PRP* s	*PW* ms	*ST* ms	*NPB*	*RT* s
	1/500	1	40	20	1
	1/350	1.4	57	20	1
	1/250	2	80	20	1
Case 1: 50% DCY	1/150	3.3	133	20	1
	1/100	5	200	20	1
	1/50	10	400	20	1
	1/25	20	800	20	1
	1/500	0.7	40	20	1
	1/350	0.7	57	20	1
	1/250	0.7	80	20	1
Case 2: low DCY	1/150	0.7	133	20	1
	1/100	0.7	200	20	1
	1/50	0.7	400	20	1
	1/25	0.7	800	20	1
	1/500	0.7	200	100	1
	1/350	0.7	200	70	1
	1/250	0.7	200	50	1
Case 3: low DCY, fixed ST	1/150	0.7	200	30	1
	1/100	0.7	200	20	1
	1/50	0.7	200	10	1
	1/25	0.7	200	5	1

3 Results

Results are summarised in Figs 5–9, where values represent the average of the minimum two-point discrimination distance in mm ± one standard deviation. Fig. 5 shows the two-point discrimination distance as a function of PRP (in log scale) for 50% DCY, and Fig. 6 shows it for low DCY, both considering the 14 subjects. Fig. 7 shows the two-point discrimination as a function of PRP (in log scale) for 50% DCY, and Fig. 8 shows it for low DCY, both for one subject over 14 trials. Fig. 9 shows the

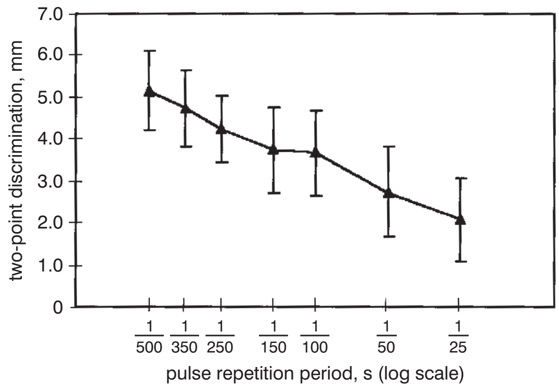

Fig. 5 *Two-point discrimination as function of PRP (in log scale) for 50% DCY, considering 14 subjects. Average discrimination distance ± 1 SD is illustrated*

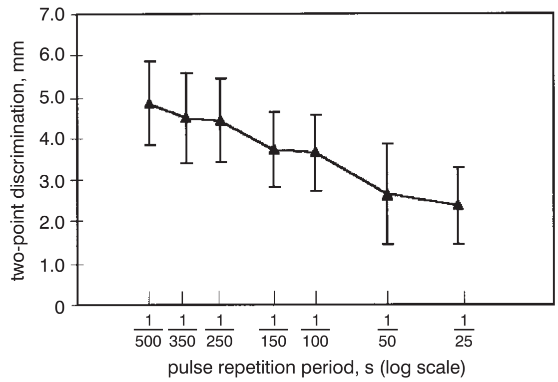

Fig. 6 *Two-point discrimination as function of PRP (in log scale) for low DCY, considering 14 subjects. Average discrimination distance ± 1 sd is illustrated*

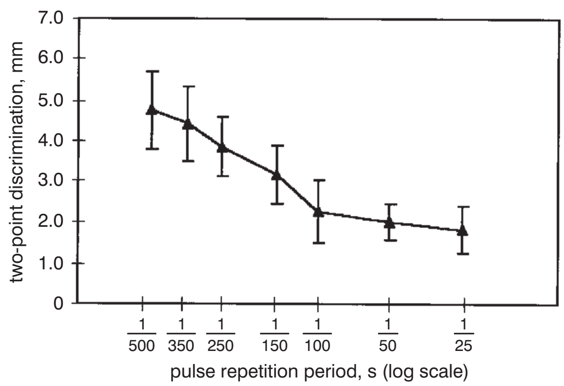

Fig. 7 *Two-point discrimination as function of PRP (in log scale) for 50% DCY for one subject, considering 14 trials. Average discrimination distance ± 1 SD is illustrated*

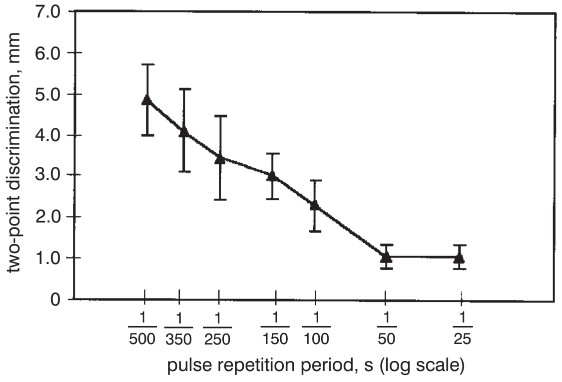

Fig. 8 *Two-point discrimination as function of PRP (in log scale) for low DCY for one subject, considering 14 trials. Average discrimination distance ± 1 SD is illustrated*

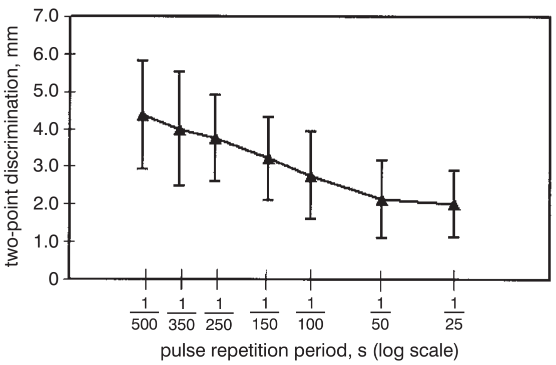

Fig. 9 *Two-point discrimination as function of PRP (in log scale), fixed ST for low DCY, for eight subjects. Average discrimination distance ± 1 SD is illustrated*

two-point discrimination distance as a function of PRP (in log scale) for low DCY and fixed ST (variable NPB), considering the group of eight individuals. In Figs 5–9, the average discrimination distance decreases (becomes better) with increasing PRP. The best discrimination results are in the range of those obtained in conventional two-point static tests that yield discrimination distances around 2–2.5 mm for the index finger (WEINSTEIN, 1968; SHERRICK and CRAIG, 1982).

The two-factor ANOVA was applied to the two-point discrimination measurements considering cases 1–3. The results show that there are statistically significant differences ($p < 0.001$) in the average two-point discrimination among different PRPs. There are no statistically significant differences between cases 1–3 (50% DCY, low DCY or ST). It was also found that factors, PRP and cases 1–3 do not interact. Results show that there are no statistically significant differences between discrimination distances for 50% DCY compared with low DCY pulses. This result is important because it means that low DCY pulses can be used, instead of 50% DCY, with no loss in two-point spatial discrimination, while saving power.

4 Conclusions

This study shows that the two-point discrimination distance for vibrotactile stimuli is better for longer than for shorter PRPs. Comparing the discrimination distance for the group of 14 individuals, as the PRP ranges from 1/25 to 1/500 s, the improvement in two-point discrimination distance is 3.0 mm for 50% DCY and 2.5 mm for low DCY. This difference represents, respectively, 240% and 200% improvement in relation to the worst discrimination capacity obtained when PRP is 1/500 s.

No statistically significant differences were found in two-point spatial discrimination between 50% DCY, low DCY and fixed ST. According to this result, by choosing a low DCY waveform, the power could be reduced with no loss in spatial discrimination capacity. These results show that the selection of PRP is important for tactile resolution, as demonstrated by the two-point discrimination test.

This study shows, in relation to previous work on sensitivity using sinusoidal waveforms, that the selection of the parameters should be made carefully to maintain a balance between the sensation threshold, which is centred on 1/250 s (VERRILLO *et al.*, 1969; CHOLEWIAK and WOLLOWITZ, 1992), and the capacity to discriminate spatially, which suggests a longer period and thus less tactile sensitivity.

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