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Effective modeling of elastic waves for haptic surface interaction

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ABSTRACT

Guided acoustic waves can be found in multiple applications as SAW-devices, NDE, hearing aids, fluid monitoring in tubes or resonance effects in structures. Among those examples, the contribution addresses the sound field design with linear elastic waves on thin display or touchscreen surfaces. Based on the principle of reversibility and the time reversal technique a simulation model was built up to calibrate the refocussing of vibrations on certain area. The main objective (of this work) is the haptic interaction of a finger with virtual elements modelled by a local vibration. The simulation bases on a finite element model of structural dynamics. In detail, the influence of elasticity, plate thickness in relation to the wavelength and the transducer positions on the wave mode selectivity are discussed. Further the numerical calibration is used to define the signals with respect to the contrast and resolution of tactile sensation in a focal point and the potential to selectively focus on multiple points at the same time. Finally two demonstrators with different frequency range are used for evaluation of the consistency of simulated and experimental excitation signals and the respective impacts on the focal quality.

Keywords: surface wave, haptic

1. INTRODUCTION

Operating a touch-screen is a matter of course in our everyday life. However, it is not taken for granted for everyone (e.g. in case of individual physical constraints) or in everyday situation (e.g. unfavorable external conditions). Then, the usability is limited due to an absent haptic feedback as in case of real keys or buttons. This contribution discusses the realization of a transient elastic touch feedback on panels and planar structures. The key components to realize a transient and local haptic feedback (pulse or vibration) with a minimum number of actuators are guided elastic waves. Here the reversibility of an acoustic wave can be used to refocus a signal on an arbitrary local position by time reversal (TR) techniques [1, 2]. Numerous application fields are connected to this technology, such as medical intervention, non-destructive testing or impact localization on touchscreen systems [3, 4, 5]. Latter technology recently gains increasing attention. Therefore the contribution addresses the local haptic feedback on panels by using acoustic transducers with randomized patterns. In the current case a limited number of acoustic transducers (Fig. 1) are placed at the edges of the structure only, omitting the touch sensitive area, since transparent display are addressed. In contrast to known TR-procedures no use is made of an experimental training stage to set up a database of plate impulse responses. Instead, the transient signal at the transducer array, that is required to selectively address a point of feedback on the panel, is gained from numerical simulations. Moreover, simulation is used to define the actuators signals with respect to the contrast and resolution of tactile sensation in a focal point and the potential to selectively focus on multiple points at the same time. As a main result the studies illustrate that an arbitrary time and spatial focusing of an elastic impulse can be established in the perceptual haptic frequency range. Due to the wavelength its simple application for larger devices (display) seems to be promising up to now.

2. METHOD

2.1 Basics: Human perception

The haptic feedback that can be felt by a human fingertip (haptic perceptual detection threshold) depends on the vertical and horizontal displacement of the surface (acoustic energy), the excitation frequency (wavelength) and the shape of the transient displacement. The lateral spatial resolution of the perceptual active area mainly depends on the wavelength.

Due to the variety of mechanoreceptors (Fig. 2) that are sensitive to different mechanical stimulus (pressure, strain, vibration, touch) there is a differentiation in static (tactile) and dynamic active (haptic) perception [6]. The tactile perception threshold of a fingertip is in the range of 1 mm. The maximum of the haptic sensitivity (Vater-Pacini-cell) can be found at a vibration frequency of $f = 40 \ldots 300$ Hz. The corresponding sensitivity levels (perceptual threshold) of the elongation at these frequencies are in the range of $\Delta x > 0.2$ µm for transversal displacement (Ruffini-cell) and $\Delta z > 5$ µm for displacements vertical to the skin surface. A cumulative movement of the finger over the surface additionally lowers the threshold (Meissner-cell). Typically, due to the ratio of the propagation velocity (larger wavelength) to the dimension of the focus point the shear mode is unsuitable despite the higher sensitivity (0.2 µm). Hence, the presented work concentrates on the basic asymmetric modes (A0) of guided elastic waves.

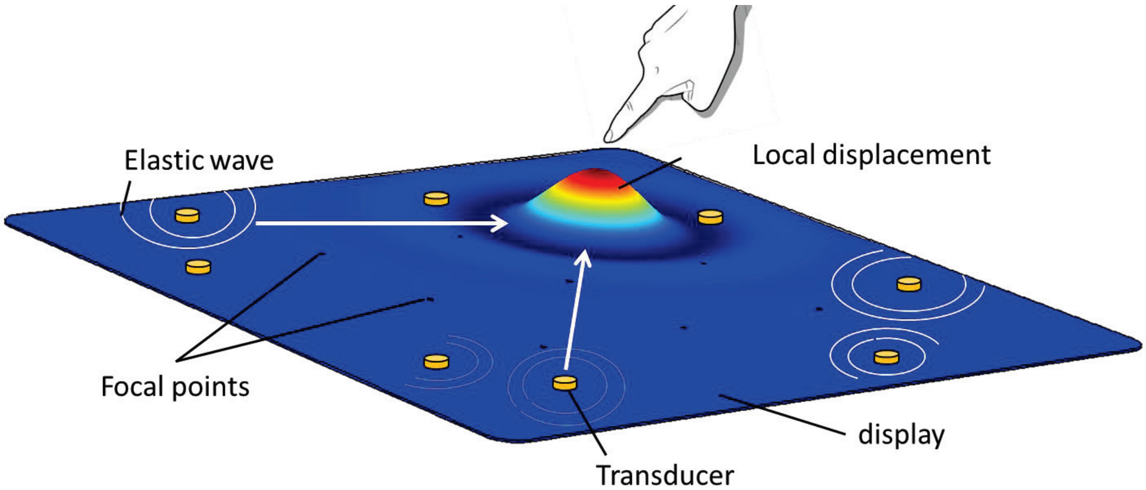


Figure 1. Schematic model (3D-simulation example) for local vibro-haptic interaction on a plate (display) by temporal and spatial superposition of elastic waves – with a reduced number of acoustic transducers.

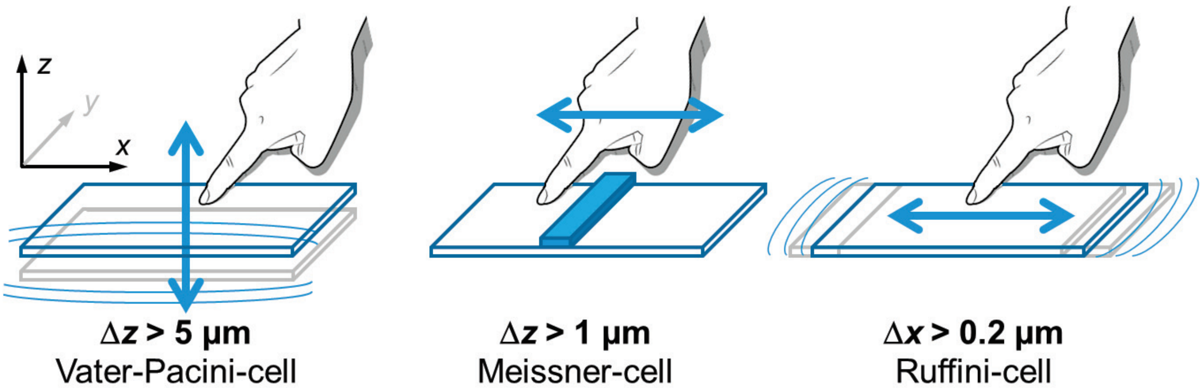


Figure 2. Classification of most common mechanoreceptors of a human hand corresponding to static (tactile) and dynamic (haptic) characteristics of a surface: (left) Vater-Pacini-cell with highest sensitivity to vibrations perpendicular to the skin in the range of $\Delta z > 5$ µm elongation and frequencies from 40 Hz to 300 Hz; (middle) Meissner-cell for active exploration of elevations of $\Delta z > 1$ µm; (right) Ruffini-cell for registration of shear vibrations $\Delta x > 0.2$ µm.

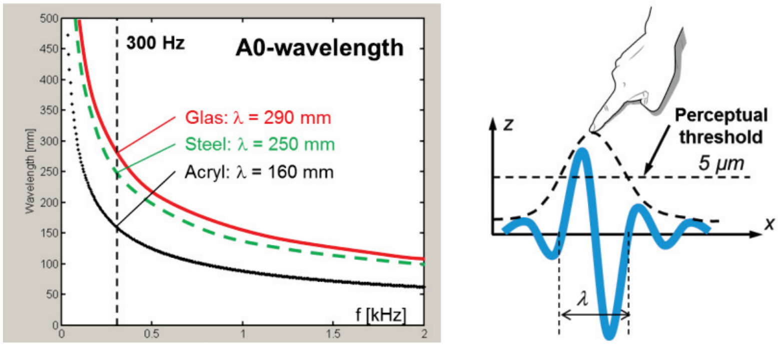


Figure 3. (a) Wavelength of asymmetric lamb-mode A0 for plates with thickness of d = 2 mm and different materials (Tab. 1). (b) Illustration of the transient waveform in relation to the wavelength, the perceptual threshold (dotted line) and effective (sensible) width of the focus.

2.2 Basics: Dispersive elastic waves

In theory, there are an unlimited number of different modes that can propagate on plate structures [9]. The phase and group velocities of each mode are dispersive and a function of frequency. Hence, it is necessary to evaluate each mode concerning its cut-off frequency, wavelength and the vertical displacement, which is supposed to be the main parameter for haptic interaction. In this case the Rayleigh-Lamb-differential equations [7, 8] that describe the elastic transient behaviour depending on the geometry (plate thickness), the elasticity and the Poisson's ratio are solved numerically using Comsol Multiphysics. The derived solution of the phase velocities enables the geometric design of the plate and the selection of single wave modes towards an optimized haptic feedback. Normally the solution is depicted within a dispersion diagram. As an example Fig. 3 a represents the dispersive characteristics of the velocities for different plates with thickness of d = 2 mm. In the range of the haptic frequency (< 300 Hz) the wavelength on selected display and surface materials varies from 160 mm to 290 mm for the asymmetric mode A0. Concerning transient elastic signals (pulse), the half of the wavelength can be regarded as the minimal dimension of the vibrating focus. In which the effective sensible focus width depends on the perceptual threshold and the energy of the signal also (Fig. 3 b).

TABLE I. MATERIAL PARAMETERS

Material	ρ [kg/m³]	c_L [m/s]	c_T [m/s]	E [GPa]	μ
Acryl	1200	2700	1200	4,76	0,38
Glass	1590	6790	4321	68.9	0.16
Steel	7850	5778	3194	205	0,28

2.3 Time Reversal of elastic waves: Technique, Principle and Challenges

The reversibility of such previous linear elastic waves is used to refocus a signal at one calibrated position to a certain time step by time reversal (TR) techniques [4, 8]. Main challenges or necessary improvements are the realization of a tempo-spatial localized short pulse on the surface with elongations in the range of the perceptual threshold ($z(t,x0) > 5$ µm) and the reduction of distributed signal clutter ($z(t,xi) < 5$ µm; on the rest of the surface) and audible acoustic noise respectively.

Principle: The ideal replication of the original impulse by time reversal of the divergent wave field requires a time reversal mirror, whose unlimited number of excitation points (transducer) forms a curve integral surrounding the original excitation point (focal point) and gathering the total transient acoustic field crossing that curve [8]. As an alternative in case of a plate (display), an unlimited number of multiple reflections (without damping) is needed to approximate the same divergent wave field by virtual sources at the reflecting boundaries and replacing the original mirror. Thereby the accurate design and selection of the transducers is no crucial precondition: Because of the interaction at the boundaries of the display different wave mode conversions occur. Due to the TR-technique only those signal path are counted which lead to a perpendicular surface elongation in the focal point only. **Challenges:** The multipath propagation of those elastic waves including reflections is crucial according to the aims: a) to use as few transducers as possible and b) to place them outside the active (transparent) area of the display. Further, because of damping and mode conversion only a limited number of excitation points and propagation path will be applicable. Hence, mainly the number and positions of the transducers need to be optimized to approximate the original haptic signal (input). The remaining challenges in realizing focal spots with guided dispersive elastic waves are:

- the providing of selectivity of propagation path and wave mode,
- the avoidance of audible acoustic noise,
- the increasing of the surface elongation in the range of the perceptual threshold and
- the adaption of the wavelength and pulse shape to the desired perceptual focal size.

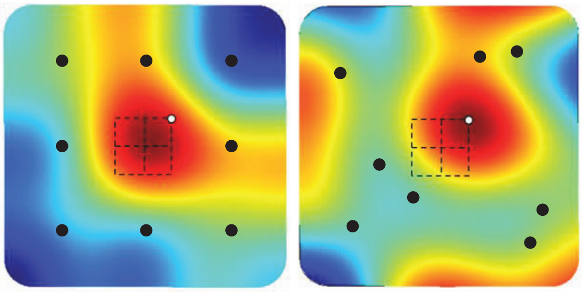
Typically common touch sensitive displays are made of glass or plastic material with a thickness in the range of 2 mm to 5 mm [3]. With the restriction of a few transducers only and because of the larger physical wavelength on such plates neither local steplike thresholds nor multiple arbitrary focus points in size and spacing of a human fingertip can be realized at the haptic frequencies (< 300 Hz). Thus, the selective generation of larger feedback spots on comparatively large plate structures seems to be realistic for now. The least energy and equivalent the smallest number of signal sources is needed for a stimulus with frequencies in the range of the maximum perceptual threshold (300 Hz). Signals with higher frequencies (and smaller focal dimensions) will need a higher excitation power due to the lower surface displacement and the decreasing sensitivity of the human finger [3]. Furthermore, additional acoustic perceptible disturbing signals would occur, which normally are not wanted. In the following example a "low cost" system is described to exemplify the applicability of the virtual calibration approach to build up a multiple spot transient haptic feedback system on "larger" transparent display or show window.

Virtual Calibration: Usually the time reversal is done by measuring the impulse response or the spectral transfer function between two separated single transceivers. This would include all physical effects and cross sensitivites within the data. Since the current application does not need an exact replication and coherence of a given haptic signal, an alternative fully automated virtual calibration by finite element modelling is used.

Therefore a three dimensional model for plates was created to solve for the stationary eigenmodes and the transient behavior of short time pulses that are excited from different multiple transducer locations, including the reflection and mode conversion at the boundaries. The parametric prestudies covered variations of the number and placement of the source points, the plates' material and thickness, the frequency and fixed and floating bearing of the boundaries. In conclusion the results showed that the material parameters don't need to be exact since the time reversed signal is reduced to the main propagation path (truncated to 30% of the time window with high signal to noise ratio) and normalized. The 1-bit-quantization [4] is not applied. In contrast the influence of source patterns (position of transducers) is more crucial and defines the virtual description of the necessary input data at the transducers in order to excite a time reversed signal at a desired focus location. Concerning a symmetric placement of the transducer it will force a symmetric (standing) wave pattern on the plate which could mask a focus displacement. The interference with the predominant symmetric wave (or elongation) pattern leads to an insufficient replication of the focal point. This elongation pattern can be homogenized by using a stochastic irregular pattern. Based on the wave field snapshots Fig. 4 illustrates the focus quality by time reversal for a regular symmetric transducer pattern and a randomized (not optimized) pattern with 8 source points. In the left figure the interference with the predominant symmetric wave pattern lead to an insufficient replication of the focal point (white circle). In contrast the irregular transducer arrangement (right figure) supports the formation of a shifted focal point.

Hence, to avoid a predominant wave pattern and to support the formation of a shifted focal point, a randomized transducer placement is necessary. For this purpose of adapting the position of an arbitrary number of transducers an optimization algorithm was realized in Matlab – including a graphical output (Fig. 5). As one criterion the variety of distances between each source point was used.

Fig. 6 depicts the steps for designing a local transient haptic feedback on transparent device (surface): Starting information are the geometry, elasticity and poisons ratio of the display. In first step the demanded basic haptic feedback signal need to be defined (in our case a short pulse with z = +/- 10 µm surface elongation). The second step covers the definition of the haptic focal area on the display (focal points matrix) and the remaining area used for transducer positioning. Therewith the optimization algorithm calculates the adapted (optimized) source positions. In the last step the automated simulation model takes the geometry, the elasticity, the poisson's ratio and the defined haptic signal into account to calculate the transient surface displacement for each transducer (latter source) position. Doing this calculation for each focal point the final excitation signal-matrix is formed. In conclusion the time reversed signals of this matrix can be used to reproduce the initial haptic signal in any calibrated focal point. Further the linear superposition of different excitation matrix enables multiple vibrating focal points at the same time, whereat the energy spreading needs to be regarded as well.



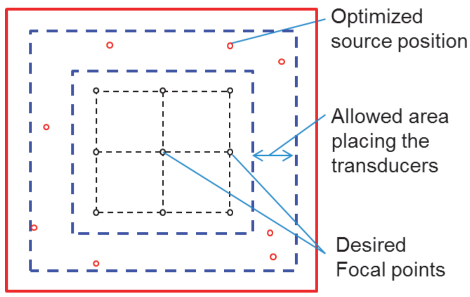


Figure 4 (left). Glass-plate (500 x 500 x 2) mm: Time reversal (simulation) with 8 transducers (excitation points) with regular (left) and randomized (right) pattern focusing on the same focal point (white spot) with a spatial offset to the plates center of $\Delta x = \Delta y = +50$ mm (wavelength at 325 Hz: $\lambda_{A0} = 290$ mm, focus timestep)

Figure 5 (right). Graphical output (Matlab) of the optimization algorithm for placing the signal sources (transducers).

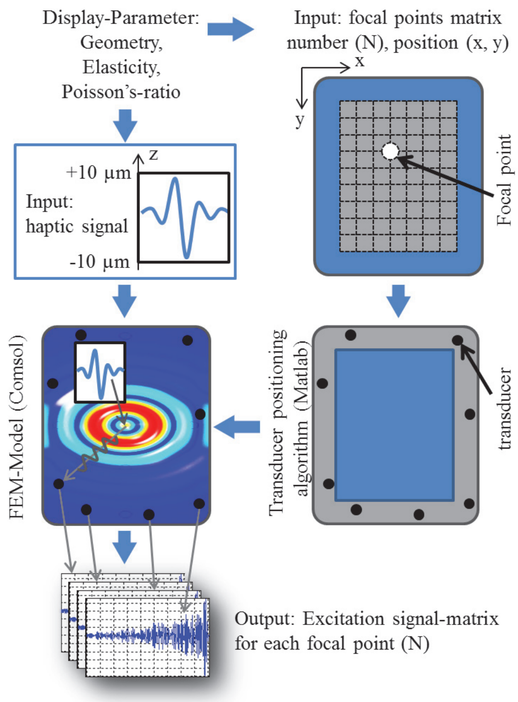


Figure 6. Scheme: Algorithmic positioning of transducers on a display and virtual calibration of excitation signal-matrix according to the desired focal point grid and haptic surface elongation.

2.4 Results, Verification and Study

As an example the snapshots in Fig. 7 depicts the focus quality on a plastic plate – with nine calibrated focus points – regarding an optimized position of eight transducers (Fig. 7 a) according to Fig. 5. Already a number of eight source points is sufficient to reproduce an ideal calibration displacement (Fig. 7 b) with perceptual adequate quality (Fig. 7 c). With this case studie amongst others it could be proven, that the forward simulation of haptic impulse are adequate to virtually calibrate a data set for time reversal haptic feedback on arbitrary focal points (Fig. 7). Where the size of the focus is determined by the physical wavelength (Fig. 3). Regarding the transient behaviour, the elongation in all other focus points, but the desired one, do not cross the perceptual threshold at any time (Fig. 8). Supplemental to the numerical studies a measurement system was established which enables the demonstration and investigation of the time reversal on plates with up to 16 independent channels. The elongation of the plate at arbitrary points is captured with a laser triangulation sensor. During the empirical prestudies a variety of geometric combination, boundary conditions, materials and mechanic transducers (piezoceramic, vibration motor, structure-borne loudspeaker, voice coil motor) were tested towards the excitation and time reversal of elastic A0 waves in the haptic frequency range (40…300) Hz.

Fig. 9 depicts one final optimized demonstrator including a plate according to the same dimensions as in Fig. 7. The device consists of a plastic plate (70x70 cm², $d = 2$ mm) clamped in a rigid frame. Eight exciter (EX60, Visaton) where coupled to the backside of the plate. A simple multichannel sound card was used as signal generator without any amplification. This robust measurement setup allowed a reliable study with a number of 70 test persons. Within the study the test persons had to distinguish different focal points (position and size) and to rate their subjective sensation of the focus quality and perception by help of a given decision table (Tab. 2).

The analysis of the study showed that

- the concept is well accepted by the majority (84%),
- a "blind" recognition of the vibration focus is done by 94% of the persons independent from age and experience with touch displays,
- the perceptual intensity shows high diversity and
- 50% had a the spatial deviation of the real focus center to the subjective center felt by the individual of less than 20 mm (which correlates to the wavelength on this plate) (Fig. 10).

In summary the empirical study verified the concept and the functionality of a vibro-acoustic haptic system for transparent surfaces, which was designed and virtually calibrated with a numerical model and an algorithm only.

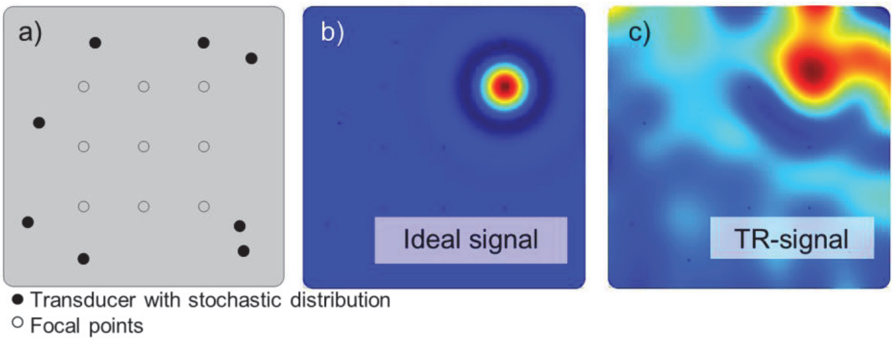


Figure 7. (a) Simulation model of a plastic plate [700 x 700 x 2]mm with 8 randomly distributed transducers and 9 selected focal points; (b) 2D-distribution of ideal localized displacement and (c) real displacement in focal point.

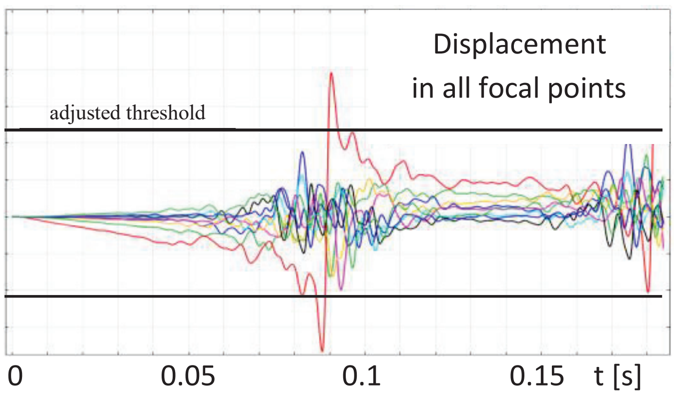


Figure 8. comparison: Normalized surface displacements Δz in all nine calibrated focal points – when focusing only one (red curve crosses the perceptual threshold only)

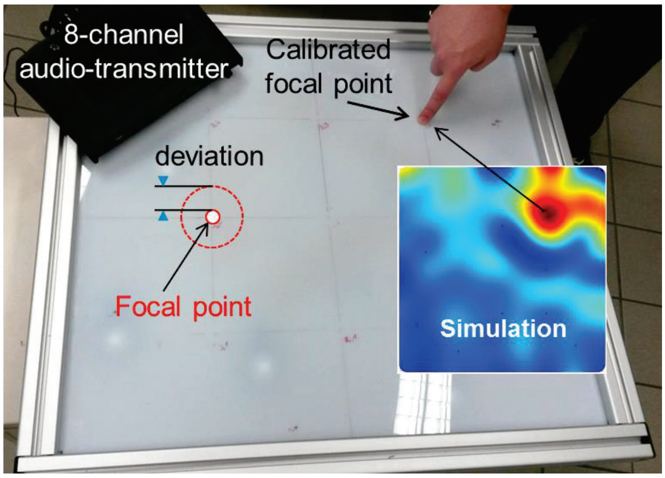


Figure 9. Demonstrator: plastic plate (700 mm × 700 mm × 2 mm) clamped in an aluminum frame; source: 8 randomly distributed transducers (Fig. 4) and a 8-channel-audio-device with integrated storage.

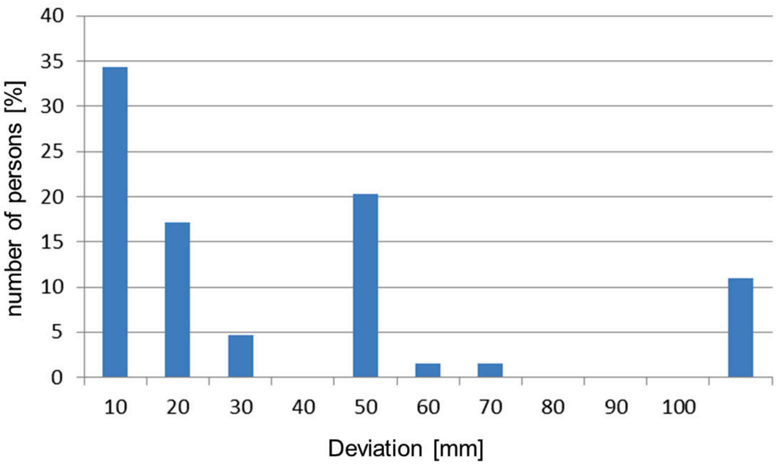


Figure 10. Spatial deviation of the real focus center to the subjective center felt by the individual

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