Inter- and intra-individual variation in earprints
Meijerman, L.

Citation
Meijerman, L. (2006, February 15). *Inter- and intra-individual variation in earprints*. Barge's Anthropologica, Leiden. Retrieved from https://hdl.handle.net/1887/4292

CHAPTER 3

INTER- AND INTRA-INDIVIDUAL VARIATION IN APPLIED FORCE WHEN LISTENING AT A SURFACE, AND RESULTING VARIATION IN EARPRINTS

L. Meijerman, N. Nagelkerke, R. van Basten, C. van der Lugt, F. De Conti, A. Drusini, M. Giacon, S. Sholl, P. Vanezis and G.J.R. Maat

Medicine, Science and the Law, accepted for publication September 2005

Abstract

We aimed to explore the level of inter- and intra-individual variation in applied force when listening at a surface, and assess the resulting variation in earprints. We further intended to identify possible sources of this variation. Forty subjects each listened twenty-four times at a surface while applied force was recorded. In between efforts the level and frequency of the target sound, and the level of ambient noise were varied. Each listening effort was characterized by two values: the mean of a series of force recordings ('functional force') and the highest force reading of the effort ('peak value'). A mixed model analysis of variance revealed that repetition during multiple efforts of listening and the level of the target sound significantly affected both values for applied force. The frequency of the target sound affected the peak value, but we assume this was due to confounding effects. The level of ambient noise did not affect applied force. To explore the correlation between values for applied force of various efforts by a single ear, the intra-class correlation coefficient was calculated. For functional force it was 0.80; for the peak value it was 0.79. To study intra-individual variation in earprints, five prints from each ear were lifted and studied. Variation in prints is discussed.

3.1 Introduction

A burglar may leave an impression of his ear at the crime scene (Dubois, 1988; Hammer, 1986; Hammer and Neubert, 1989; Hirschi, 1970a,b; Pasescu and Tanislav, 1997; Scaillet, 1971). This latent earprint can be made visible using techniques similar to those used for lifting fingerprints, and has potential for forensic investigations (Van der Lugt, 2001; Meijerman et al., 2004c). A prerequisite to using earprints for identification is an estimation of the probability of encountering seemingly indistinguishable prints from different ears. This estimation of 'false positive probability' requires insight into the variability in various prints of a single ear (Champod et al., 2001).

A potentially important source of intra-individual variation in earprints is variation in applied force when listening (Neubert, 1985; Saddler, 1996). We have suggested that the necessity for 'functional' (effective) listening will, in practice, limit the range of applied force when listening (Meijerman et al., 2004c). To explain this, we hypothesized that applied force may reflect a balance between the aim to create a seal with the ear on the surface to optimize hearing, and the inclination to minimize discomfort to the ear or cheek. Although we anticipate that the degree to which achieving a complete seal with the ear on the surface is pursued may possibly depend on variables such as the level or frequency of the sound one is trying to hear, or on the level of ambient noise, it would imply that individual anatomy of one's ear would play a key part in determining the functional force range.

With this study, we aim to explore the concept of a personal 'functional force range'. How do inter- and intra-individual variation in applied perpendicular force compare? Can we identify factors that influence applied force, and if so, to what extent? Singling out factors that affect applied force, therefore inducing intra-individual variation in prints, may ultimately aid in determining the extent of realistic variation in prints by a single ear. Apart from the level and frequency of the target sound, and the level of ambient noise, repetition during consecutive listening efforts was investigated for its effect on applied force. A significant effect of repetition – a reduction in applied force during consecutive listening efforts – may be an indicator of comfort (or lack thereof) influencing the hypothesized force balance.

Differences between force applied by the left and the right ear were also studied. Inter-individual variation was addressed as well, including comparisons between the sexes and left/right handedness. Intra-individual variation in earprints, allegedly resulting from variation in applied force, was examined and will be discussed.

3.2 Experimental design

To assess the variation in applied perpendicular force when listening at a surface, both between individuals, and between individual attempts of one person under different conditions, forty subjects listened at the surface of a ‘listening box’. This listening box had loudspeakers placed on the inside and a weight scale[5] assembled in one of its vertical surfaces. Both the scale and the speakers were connected to a computer. The scale served as the listening surface, thus measuring applied perpendicular force at irregular intervals of 0.35 to 0.8 seconds[6] (Kieckhoefer, 2002). Various sound files were played inside the box to serve as a target sound. Each sound file consisted of a short introduction, an easy-to-answer question[7], and a repetition of this question. All files lasted seventeen to twenty seconds and were normalized in order to be similar in amplitude. Files were saved at three different volume levels: ‘soft’ (51-52 dB), ‘medium’ (54-55 dB) and ‘loud’ (56-57 dB)[8], enabling a test of the effect of target sound amplitude upon applied force. During the test sessions, it appeared that the target sound was always audible, although the degree of understanding of what was asked varied among subjects.

In order to test the effect of target sound frequency, both a male and a female voice were used. A complex of sounds was recorded in a busy restaurant, and saved at two different levels (‘peaks up to 50 dB’ and ‘peaks up to 60 dB’, measured at the position of the listener). These files were played on a stereo-player placed in the vicinity of the listener, enabling a test of the effect of added ambient noise on applied perpendicular force, as compared with applied force during relative silence (36-37 dB).

To restrict the number of combinations of these variables, the condition ‘male voice and

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[5] LUTRON GM5000; accuracy 0.3% + 1d (specifications by manufacturer).

[6] Force applied by a listener in fact consists of a component that is perpendicular (normal) force, and a smaller component that is lateral force. The readings of the scale provided the measurements of perpendicular force with some lateral force additions. The error was found to be relatively small (Kieckhoefer, 2002).

[7] For example “Where were you born?” or “What is your favourite colour?”

[8] The sound level was measured inside the box.

medium level of target sound; medium level of ambient noise' was chosen as a standard. Each of the three variables (i.e., level and frequency of target sound and level of ambient noise) was changed independently, resulting in six possible conditions (Table 3.1). All combinations were tested for the left and right ear separately, and the order in which they were varied differed between the left and the right ear. The nature of the actual question was varied randomly. The resulting twelve combinations were repeated and tested in the same order as the first series of twelve, adding up to the total of twenty-four listening efforts per person. This series of efforts was divided into sub-series of three: each subject listened three times while using the left ear first, followed by three using the right ear, and so on. To equalize the effect of comfort for all subjects, the sound box was adjusted to the stature of each subject. If applicable, subjects were asked to remove earrings and glasses.

We also wanted to examine intra-individual variation between force applied by the left ear and that by the right ear. As we were interested in ascertaining whether or not any correlation could be observed between force measurement and handedness, the latter was recorded for each subject. Each listening effort was recorded as a series of consecutive force readings. The earprints that resulted from the first five efforts by each ear were dusted using fine aluminium powder, and preserved on Black Gel Lifters.

Table 3.1 *Six conditions under which was listened in order to explore the effect of volume level and frequency of the target sound, and of volume level of ambient noise, on applied force.*

'Standard'	1. Male voice, 54-55 dB target sound; 50 dB ambient noise
Tested variable: Level of target sound	2. Male voice, 51-52 dB target sound; 50 dB ambient noise 3. Male voice, 56-57 dB target sound; 50 dB ambient noise
Tested variable: Level of ambient noise	4. Male voice, 54-55 dB target sound; 36-37 dB ambient noise 5. Male voice, 54-55 dB target sound; 60 dB ambient noise
Tested variable: Frequency of target sound	6. Female voice, 54-55 dB target sound; 50 dB ambient noise

3.3 Analytical methods

Data from one of the forty subjects participating in the experiment were excluded because of external disturbances during the test session. Additionally, of the remaining thirty-nine subjects (thirteen women and twenty-six men), the data from four individual efforts were lost due to technical problems. The remaining 932 listening efforts resulted in a series of force readings (i.e., readings of load in grams) (see Fig. 3.1 for examples).

For each series – representing one listening effort – we calculated the mean and the standard deviation for two intervals comprising twelve force readings each. One interval approximately represented the period during which the question was being played; another interval towards the ending included the repetition of the question. For the majority of efforts, the standard deviation was lower for the second interval than it was for the first, indicating that during this interval applied force was more balanced than it was during the earlier interval. It was then assumed that the mean of the second interval approached the balance – as hypothesized in the introduction – more than the mean of the first interval did. For standardisation, the final two force readings of each effort were first excluded, as these were usually either relatively low because the subject was abandoning the listening surface, or relatively high as a result of a ‘push’ subjects occasionally gave themselves when abandoning the surface. The calculated mean of the twelve force readings prior to these last two readings will be referred to as the ‘functional force’ – ‘resulting from functional listening’ – in the remainder of this text.

We also characterized each listening effort by the highest force reading of the entire series of readings, as a moment of relatively high force may also influence the appearance of an earprint. We noted that such moments often occurred relatively early into a listening effort, so did not necessarily result from functional listening. We therefore anticipated that the highest force reading of an effort might be affected differently by the tested variables. The value will be referred to as ‘peak value’ in the remainder of the text.

Both values characterizing a single effort, i.e., the functional force and the peak value, were analysed independently in order to estimate the effect of the various variables on applied force. Prior to defining these variables, we had calculated for each of the twenty-four listening efforts the average functional force for all subjects combined, as well as the average peak value, in order to detect a possible pattern resulting from repetition of efforts (Figure 3.2). The functional force values appeared to show a tendency to increase over the first six consecutive efforts, and a tendency to decrease after the sixth. The peak values showed a somewhat similar behaviour. Values also appeared to be relatively low for several first efforts of a sub-

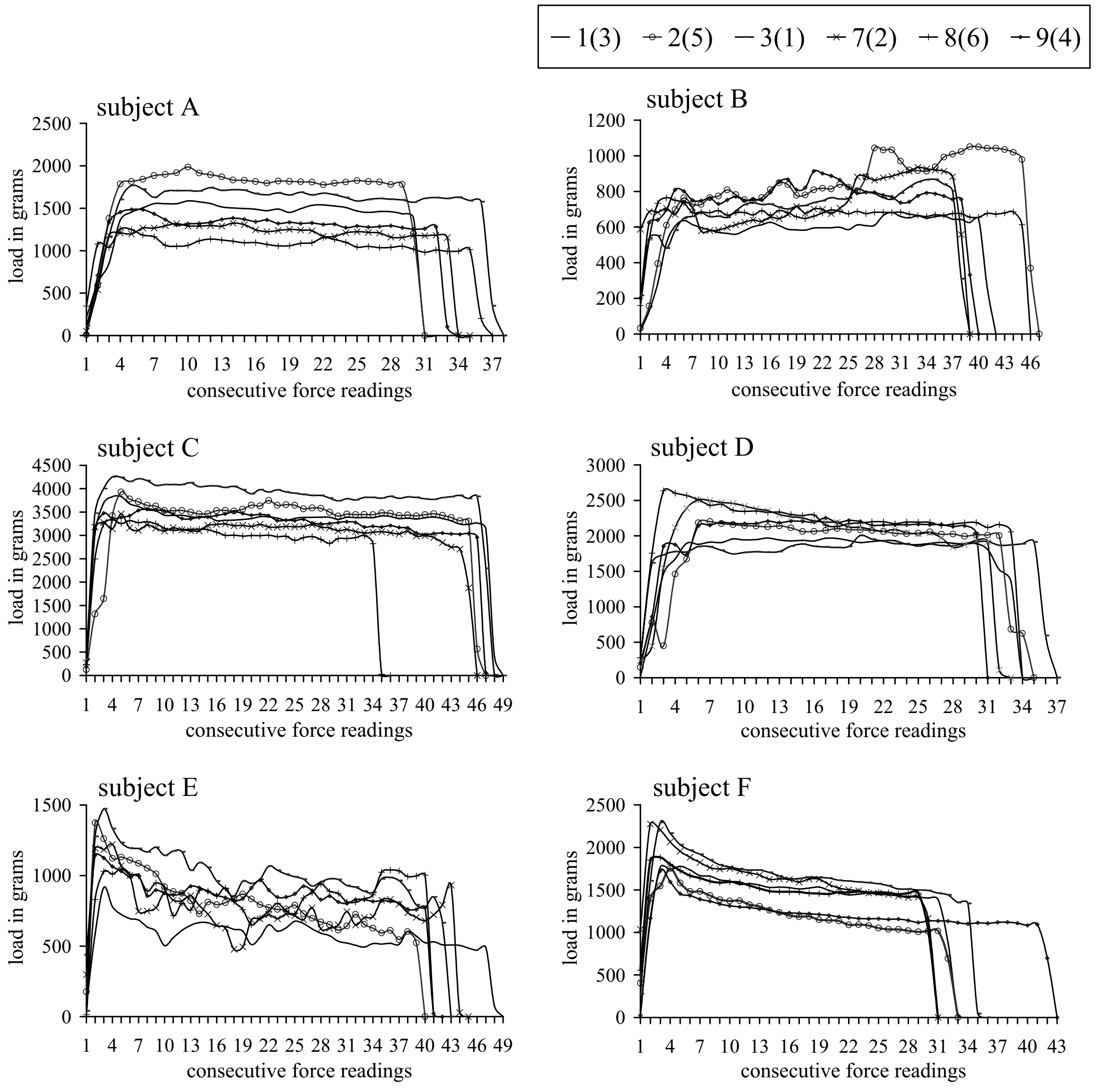

Fig. 3.1 *Applied perpendicular force during the first six efforts made by the left ear (efforts 1 to 3 and 7 to 9 of 24) for six subjects (A-F).* Conditions for each effort (see Table 3.1) are provided in parentheses in the legend.

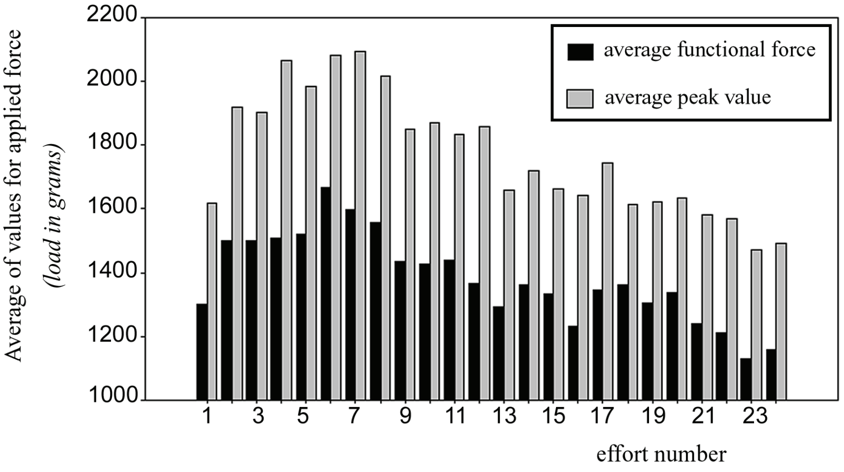

Fig. 3.2 *Average applied force (both functional force and peak value) of all subjects combined for each of the 24 efforts.*

series of three efforts by one ear. We therefore introduced variables indicating both the position in a sub-series as well as the position in the series of twenty-four. For the latter we tested both a linear and a quadratic term. We applied a mixed model analysis of variance, using SPSS (version 11.5) to explore the effect of the different tested factors on both values for applied force. Random variables were: 'the subject' [some subjects applied more force than others] and the interaction between ear and subject [some subjects tended to apply more force with one ear than with the other]. Fixed factors were: frequency of target sound [male or female voice], level of target sound ['soft' (51-52 dB), 'medium' (54-55 dB) or 'loud' (56-57 dB)], level of ambient noise ['36-37 dB', 'peaks up to 50 dB' or 'peaks up to 60 dB'], left or right ear, left or right handedness, sex of subject, and dummy variables to indicate the position within a series of three or four[9] consecutive efforts by the same ear ('position sub-series'). As covariates we tested two functions of 'position of the effort in series of twenty-four', viz. a linear term ('position') and a quadratic term ($(\text{position} - 6)^2$). The cumulative

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[9] Occasionally a fourth effort in a sub-series replaced an earlier effort that was dismissed due to irregularities during the test-session, such as, for instance, uncontrolled ambient noise.

effect of the latter three variables was thought to adequately describe the alleged effect of repetition (as assumed from the averaged results of all subjects; Fig. 3.2). The model tested in the mixed model analysis may now be described as:

$$Y_{ijkl} = \alpha + \gamma_{\text{frequency target sound}} + \gamma_{\text{level target sound}} + \gamma_{\text{level ambient noise}} + \gamma_{\text{ear}} + \gamma_{\text{handedness}} + \gamma_{\text{sex}} + \gamma_{\text{position sub-series}} + (\beta_{\text{position}} * \text{position}) + (\beta_{(\text{position-6})^2} * (\text{position - 6})^2) + \varepsilon_i + \varepsilon_{ij} + \varepsilon_{ijkl}$$

where i denotes the subject, j the ear, k the condition, l the first or second time for a condition to be tested, α the intercept, γ the estimated effect of a fixed factor, β the estimated effect of a covariate, and ε a random effect.

The hypothesis 'H_0: $\gamma_{\text{frequency target sound}} = \gamma_{\text{level target sound}} = \gamma_{\text{level ambient noise}} = \gamma_{\text{ear}} = \gamma_{\text{handedness}} = \gamma_{\text{sex}} = \gamma_{\text{position sub-series}} = \beta_{\text{position}} = \beta_{(\text{position-6})^2} = 0$' is tested against '$H_1$: any of above terms $\neq 0$'. H_0 will be rejected if the probability of obtaining the data when H_0 applies is less than 0.05 for any of the variables.

To explore the correlation between the values for applied force of the various efforts by the same ear we used the intra-class correlation coefficient, which is a measure of the correlation between related interchangeable objects. The intra-class correlation coefficient ρ is estimated by the equation $\rho = \sigma_\pi^2/(\sigma_\pi^2 + \sigma_\varepsilon^2)$, where σ_π^2 denotes the between-individuals variance and σ_ε^2 the within-ears (error) variance (Fisher, 1925). A univariate analysis of variance (SPSS, GLM procedure) was used to estimate these variance components, adjusting for factors such as the frequency and level of target sound and the level of ambient noise (to avoid these factors contributing to the error variance). To estimate the difference between left and right ears of subjects, a univariate analysis of variance was used as well. Interaction effects of subject*ear were estimated and compared with data on left or right-handedness.

Finally, intra-individual variation in lifted earprints of the first five efforts by each ear was studied, making use of transparency overlays. A number of prints were further digitised and compared on the computer, using image-processing software.

3.4 Results and discussion

3.4.1 Applied force within a single effort

The value for functional force and the peak value of each effort appeared to be highly correlated (Pearson's correlation coefficient: 0.921, p-value: 0.000). This means that a high peak value was often combined with a strong functional force. This is not as obvious as it may appear, as peak values were very often reached within the first few force readings during which we did not yet expect functional listening. In 18% of all efforts, the peak value had been reached within the first two consecutive force readings, in 63% it had been reached within the initial four, and in 78% within the initial six. In 2% of all efforts, the peak value was not reached until the last two force readings.

Although irregular sampling of the weighing scales blurred actual time that passed before peak values were recorded, it seemed that the position of the peak value on the force-curve of one effort was not randomly distributed among the subjects. This suggests that this aspect of one's listening technique may be somewhat personal. Further knowledge on behaviour of applied force within single efforts (i.e., inter- and intra-individual variability in the shape of force-curves as depicted in Fig. 3.1a-c), may provide us with a tool to detect fraudulent attempts of delivering reference prints by applying excess force to intentionally blur the print.

3.4.2 Inter-individual variation in the functional force and peak value

Great variability between subjects was found in the calculated functional force. The highest value was 3956g for one subject, while 220g represented the lowest value for another. The mean of all efforts was 1381g (SD: 685). The peak value varied even slightly more: between 4732g for one subject and 342g for another. The mean peak value was 1772g (SD: 818). Although at first glance it appeared that women generally applied slightly less force than men (Table 3.2), the mixed model analysis of variance revealed that the difference was not significant. No significant difference occurred between left or right-handed subjects either. Inter-individual variance data, therefore, did not lead to rejection of the null hypothesis.

3.4.3 Intra-individual variation in the functional force and peak value

Both values for applied force showed intra-individual variation, the extent differing

Table 3.2 *Inter-individual variation: p-values for two fixed factors and mean of values for functional force and the peak values.* P-values smaller than 0.05 are considered significant.

Variables	Functional force	Peak value
Sex of subject		
p-value	0.125	0.319
Mean of male efforts (n= 624)	1497g (SD: 676)	1861g (SD: 805)
Mean of female efforts (n= 308)	1172g (SD: 654)	1610g (SD: 818)
Right or left handedness		
p-value	0.456	0.483
Mean of right-handed efforts (n=764)	1430g (SD: 715)	1823g (SD: 848)
Mean of left-handed efforts (n= 168)	1190g (SD: 514)	1575g (SD: 655)

between subjects. Ranges of functional force (i.e., the greatest difference between two efforts by the same ear) varied between 2142g for one subject and 185g for another. For the peak value, ranges varied between 3000g and 271g. It appeared that the span of an ear's force range correlated, to some extent, with the amount of applied force. Generally, the range of applied force by one ear appeared smaller for subjects who applied relatively little force, as compared with those who applied more.

The results of the two separate mixed model analyses of variance (effect on functional force and effect on peak value) are shown in Table 3.3, which provides the calculated p-values for fixed factors and covariates, and the estimated effect of variables that significantly affected applied force. The null hypothesis was rejected on the basis of the outcome for various fixed variables and covariates testing intra-individual variation.

The level of target-sound appeared to have significantly influenced applied force. Particularly the lowest level of target-sound (51-52 dB inside box) generally evoked an increase in applied force by our subjects. The level of ambient noise did not appear to have induced significant changes in applied force, and the results for target-sound frequency were somewhat ambiguous. Variation in frequency appeared to have affected the peak value more than the functional force. We did not digitally alter frequency to achieve the effect of a male

Table 3.3 *Intra-individual variation: p-values for five fixed factors and two covariates, and the estimated effect (g) of variables that appeared to significantly affect applied force*. P-values smaller than 0.05 are considered significant.

Variables and parameters	Functional force		Peak value	
	p-value	Estimated effect (g)	p-value	Estimated effect (g)
Level of target sound	0.000		0.000	
– 'soft'		+183		+265
– 'medium'		+ 27		+51
– 'loud'		0[a]		0[a]
Level of ambient noise	0.136		0.621	
Frequency of target sound	0.088		0.035	
– 'male voice'				0[a]
– 'female voice'				+102
Position effort in sub-series	0.001		0.001	
– 'first'		-81		-206
– 'second'		+41		-47
– 'third'		+71		-69
– 'fourth'		0[a]		0[a]
Position effort in series of 24	0.027	-7	0.004	-12
$(\text{Position-6})^2$	0.001	-0.7	0.000	-0.9
Left or right ear	0.752		0.234	

[a] This parameter is set to zero as it is redundant.

and female voice, but used two different, real voices. We therefore cannot rule out an effect generated by differences in clarity of speech between the two voices. Also, due to the experimental design, there were more questions asked by the male voice. The change to female voice from previous male voice questions may therefore have induced changes not related to the change of frequency, e.g., surprise or confusion. This would explain a significant effect on the peak value, as peak values were often recorded in the initial seconds.

All three variables purported to describe the effect of repetition appeared to be significant. When comparing the estimated effect for efforts one to three of the variable indicating the position in a sub-series, it appeared that particularly force applied during the first effort after a switch of ears was relatively low. The significance of the quadratic function confirmed that during the initial six efforts values tended to increase with every new effort, while further along the values tended to decrease (see Fig. 3.2). We assume that this decrease in applied force after the sixth effort is due to decreasing comfort. We further suspect that the relatively low values during the first six efforts, as well as during the first efforts after a switch of ears, resulted from increased caution. Subjects generally appeared to be positioning their ears more carefully during the first few efforts, and again after a switch of ears, applying less force during the entire effort.

From the mixed model analysis, it appeared that there was no significant difference between left or right ear efforts in general (Table 3.3). This analysis did not expose potential differences in applied force by two ears of one subject. A univariate analysis of variance, however, showed that for ten subjects, applied functional force significantly differed between the left and right ear. For twelve subjects, the peak values varied significantly between both ears. For each of these subjects it was recorded if they were left or right-handed. There appeared to be no correlation between left or right-handedness, and which of the ears applied the greatest force (Table 3.4).

The results of the mixed model analysis of variance explained – to some degree – intra-individual variation in applied force. To reveal the degree of correlation between different force-measurements of the same ear, we also calculated the intra-class correlation coefficient. This was done using the estimated variance components provided by a univariate analysis of variance. The intra-class correlation coefficient is close to 1 when intra-individual variability is very small compared with inter-individual variability. After adjusting for tested fixed factors and covariates, the intra-class correlation coefficient was calculated to be 0.80 for functional force. For the peak value, it was 0.79. This indicates that intra-individual variation in both values for applied perpendicular force is relatively low as compared with the inter-individual variation. We may therefore theorize about the existence of a personal functional force range, probably resulting from the force needed to create a reasonable seal with the ear on the surface.

The significance of the various variables used to test the effect of repetition, when explained as a separate effect of both caution and discomfort, would further corroborate the hypothesis that the level of comfort that is experienced by the subject also influences applied force. Both the amount of force needed to create a reasonable seal, and the amount of force that would cause discomfort, would greatly depend on the anatomy of the subject's ear, although one can imagine that this could further depend on external factors such as the nature of the listening surface (e.g., wood, glass, metal). This factor was not tested during our experiment. The significance of the level of target sound on functional force implies that further external factors may influence applied force. Possibly this particular factor has influenced the need for a more or less complete seal.

Table 3.4 *Data on which is the 'forceful ear' compared with handedness (for subjects that applied significantly more force with one ear than with the other).*

	Left-handed	Right-handed
Functional force significantly different (n=10)		
– Right ear > left ear (n=3)	0	3
– Left ear > right ear (n=7)	1	6
Peak value different (n=12)		
– Right ear > left ear (n=6)	1	5
– Left ear > right ear (n=6)	0	6

3.4.4 Resulting intra-individual variation in earprints

When comparing various earprints obtained from one ear, it appeared that what we considered realistic variation in applied perpendicular force, indeed often resulted in visible changes in the appearance of prints. Various earprints were scanned and compared digitally to reveal the degree of similarity. In scans of prints that were made using low force colours were inverted, while in those made using high force they were not. When the latter prints were superimposed onto the first, those areas appearing white are representations of the print made at higher force, while those in black are representations of a print made at lower force. Areas common to both prints appear grey. Fig. 3.3 shows two different prints by each of three ears, as well as matched images of these prints.

Equal intra-individual variation in applied force did not always lead to equal intra-

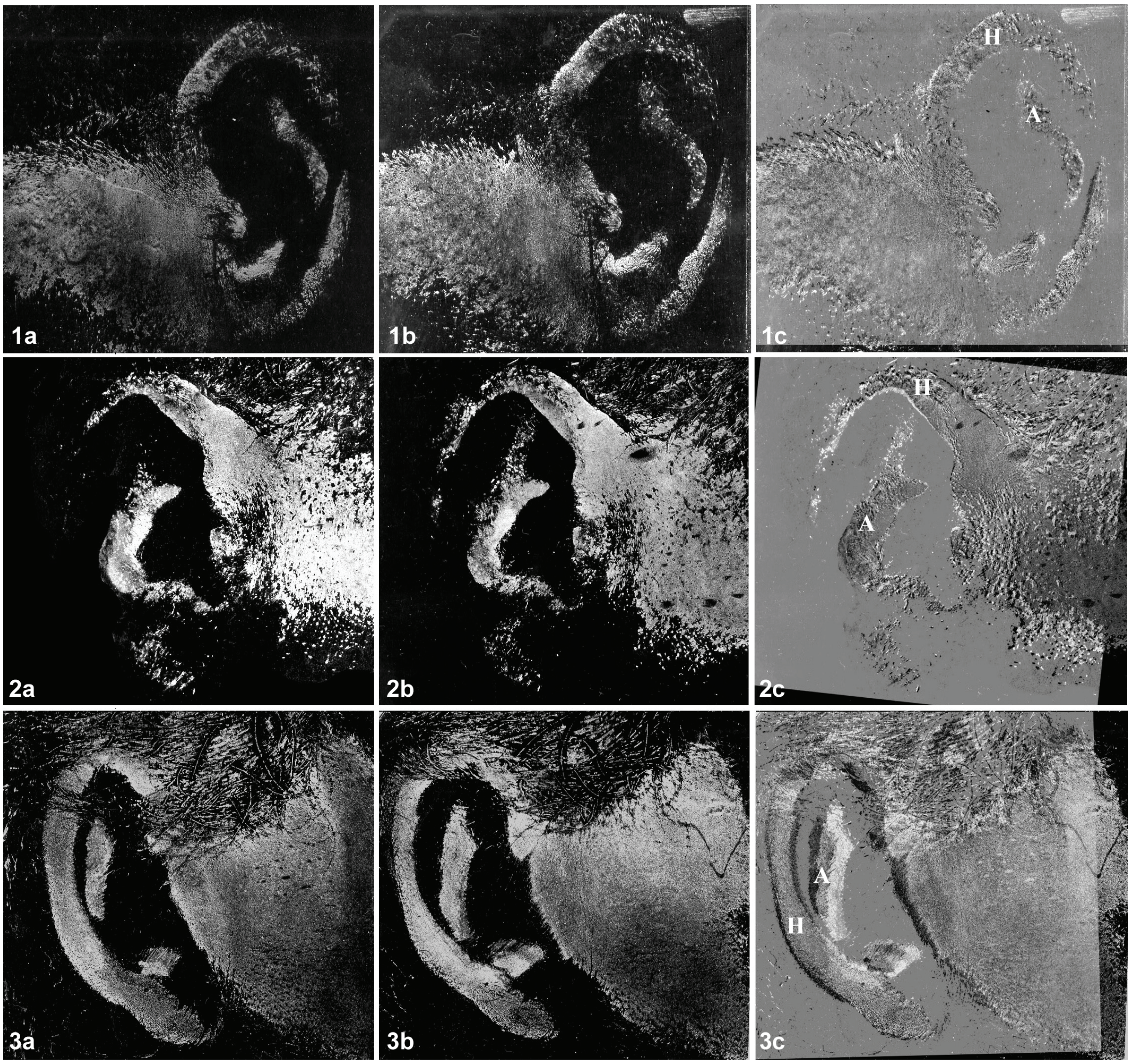

Fig. 3.3 *Two different earprints (a, b) and 'matched' prints (c) of three different ears (1, 2, 3).*
A= Anthelix; H=Helix. Values for applied functional force (g) and, in parentheses, the peak value (g) are:
1a. 1174 (2450); 1b. 2298 (3805); 2a. 2551 (2794); 2b. 3697 (3816); 3a. 3021 (4341); 3b. 3126 (4075).

individual variation in the earprints. For some ears, a change in force appeared to have a relatively great effect on the prints, while for other ears relative large changes in force seemed to have little effect on the appearance of the prints (see, for instance, 1a-c in Fig. 3.3). Not only the amount, but also the nature of intra-individual variation in prints varied between ears. When comparing the prints of the second ear in Fig. 3.3 (2a-c), it appeared that the imprint of the anthelix and helix both increased in dimensions with increased force. The superior and inferior parts of the ear, however, appeared to have a dissimilar reaction to increased force, resulting in a shift of position of the upper half of the print as compared with the lower half. We suspect that this is due to a difference in flexibility of the superior and inferior parts of the auricle. When comparing the prints of the third ear in Fig. 3.3 (3a-c), it appeared that the overall width of the earprint increased with a change of applied force, presumably due to flattening of the auricle. It, however, also appeared that the dimensions of the imprint of the anthelix increased with higher force, while the imprint of the helix decreased in width. We presume that this is due to a change in force distribution.

3.5 Conclusion

Realistic intra-individual variation in applied force may indeed cause visible variation in the appearance of various prints by one ear. From the observed range of inter-individual variation in applied force, as compared with the observed range of intra-individual variation, it became clear that obtaining earprints whilst applying a fixed amount of force would often fail to yield ‘true’ (functional) earprints. It is therefore recommended to obtain reference prints from natural listening efforts by the suspect, as this would increase the chance of obtaining a realistic earprint. This would facilitate comparison between a crime-scene print and the reference print. It could further augment the chance of recovering the print from a database of digitised prints during potential future automated searches.

To increase the probability of obtaining (realistic) intra-individual variation in earprints – either reference prints of a suspect, or research prints for investigating the extent of this variation – one could further consider exploiting the variables that significantly affected applied force. Repetition affected force during multiple efforts of listening, and so did the level of target sound. As force was generally lower during the first effort, one could for instance provide a relatively loud target sound during this effort while decreasing this level for a later effort in order for one variable to enhance the effect of the other.

Acknowledgements

We would like to thank the department of Criminal Investigation of the Utrecht Police for allowing us to use their facilities while testing. We further would like to thank all participants for their time, patience and effort, Gert van Antwerpen, Hendrik van Antwerpen and Ruud van Munster of TNO (Delft, the Netherlands) for normalizing the sound files and technical advise, Dr. M. Ingleby and H. Kieckhoefer of the University of Huddersfield (UK) for their contributions to our knowledge on applied perpendicular force and, finally, André Hoogstrate, Ivo Alberink and Arnout Ruifrok of the Netherlands Forensic Institute (Den Haag, the Netherlands) for their valuable comments on an earlier draft of this text.

- *In order to create conditions that increase the probability of obtaining (realistic) intra-individual variation in earprints, one could exploit the variables known to affect applied force.*
- *Knowledge on the behaviour of applied force within single listening efforts may provide us with a tool to detect fraudulent attempts of delivering reference prints by applying excess force to intentionally blur the print.*
- *It is advised that suspects should be actually listening at a surface when their earprints are enrolled.*