How Observer Conditions Impact Earthquake Perception *(2014)*

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Introduction

Intensity scales define the criteria used to determine different levels of shaking in relation to environmental effects. Objective evaluations of low intensity degrees based on transient effects may be difficult. In particular, estimations for the number of people feeling an earthquake are critical, and are qualitatively described by words such as “few”, “many”, and “most” for determining various intensity levels. In general, such qualitative amounts are converted into specific percentages for each macroseismic scale. Additionally, estimations of macroseismic intensity are influenced by variables that are mentioned in macroseismic scale degree descriptions. For example, the Mercalli-Cancani-Sieberg (MCS; Sieberg, 1930) and the Modified Mercalli Intensity (MMI) scales (Wood and Neumann, 1931) describe the intensity II as “Felt only by a few people, extremely susceptible, in perfectly quiet situations, almost always on the upper floors of buildings”. Another example is the European Macroseismic Scale (EMS) (Grunthal, 1998) that describes the intensity V as “felt indoors by most, outdoors by few. Many sleeping people awake”.

In this work, we focus on two variables referred to as people’s physical “situation” (what were you doing?), here categorized as “sleeping”, “at rest”, or “in motion”; and the observer’s “location”, here categorized as “higher floors”, “lower floors”, and “outdoors”. Both variables have a partial influence on intensity assessments because they condition vibration perception. However, it is important to study, using an experimental method, the weights of these variables in the quantification of felt effects. Musson (2005a) also recognized the influence of such conditions on the number of people feeling an earthquake, stating that the proportion of people in different conditions “are generally difficult to quantify in any case”. Today, we have a large amount of data available through the macroseismic web site “haisentitoilterremoto” associated with specific observer conditions. Using this data, a study of these effects is possible. For this analysis, we placed attention on transitory effects that, in the past, could not be easily studied due to the intrinsic difficulty in collecting this type of data. The aim of this work was to specifically analyze and quantify how the observer's "situation" and "location" influence earthquake perception suggesting a new scale description that can be easily used for low intensity estimation.

Data

The analysis was conducted using about 250,000 macroseismic questionnaires received through the internet for earthquakes in Italy of medium to low magnitude that occurred from June 2007 to October 2012 at a depth shallower than 20 km and with local magnitude M_L from 3 to 5.9 (Fig. 1). The analyzed questionnaires pertain to 793 earthquakes located in the Italian territory, most of the events (778) had M_L between 3 and 5, and a few (15) had a magnitude greater than or equal to 5 (Figs. S1-S2 and Tab. S1, available in the electronic supplement to this article). The internet-based macroseismic questionnaire used for the study is managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV), and is available at www.haisentitoilterremoto.it ("hai-sentito-il-terremoto?" means "did you feel the quake?"). The online questionnaire is basically compiled by volunteers, although a group of permanent compilers (approximately 20,000, homogeneously distributed in Italy) are alerted via e-mail after the occurrence of an earthquake near their municipality. The presence of a question that asks if an earthquake was felt or not felt provided us with a set of "not felt" data. Even if the data are under-sampled with respect to reality, as generally occurs using online surveys (Boatwright et al., 2012), "not felt" data actually represented almost half of the database.

The questionnaire lists the questions needed for estimating macroseismic intensity (Sbarra et al., 2010). In particular, answers to the question regarding vibration perception consider four levels of progressive shaking intensity ("not felt", "weak", "moderate", or "strong"). Other questions are useful for describing the "situation" and the "location" of the observer. Concerning the question "What were you doing?" respondents can choose one of the following: "sleeping", "at rest", "in motion", or "do not remember". Data for the "do not remember" option were discarded. For observer location, the online choice was either "outdoors" or "inside a building". Regarding the “inside a building” option the respondent was asked about floor position. At present, the greatest portion of the questionnaire pertains to observations made for the first or second floor (67%). Data regarding the outdoors represented less than 10% of responses. For this “location” we did not offer a “sleeping” option.

Analysis and results

We created several graphs (Fig. 2, S3, available in the electronic supplement to this article) for various magnitudes showing the earthquake felt percentages measured for all observers separated for the couple “situation - location”, here referred as “condition” and plotted versus the hypocentral distance. In each window (20, 30, or 40 km wide for Fig. 2a, b, and c-d respectively), the felt percentage was calculated and placed at the distance corresponding to the window center. In these graphs we searched for the existence and the quantification of joint effects on the “situation” and “location” of earthquake perception. The magnitude ranges considered were from 3 to 3.9 (Fig. 2a), from 4 to 4.9 (Fig. 2b), from 5 to 5.4 (Fig. 2c), and from 5.5 to 5.9 (Fig. 2d). We grouped the floors into two classes with similar effects (Sbarra et al., 2012), thereby separating lower floors (basement, low ground) from higher floors (from 1 to 6). Since in Italy buildings with six or more stories are rarely present and the amount of data is consequently too low to be meaningful we did not analyze floors higher than six. Each of the plotted felt percentage values accounted for at least 20 questionnaires (for conditions involving the “outdoors”) up to nearly 10,000 (Fig. S3, available in the electronic supplement to this article). In the figures presented, the experimental points are connected with a smooth line only for interpretation. Since data for “not felt” were not well sampled because it is unlikely that a person not feeling an earthquake will visit an internet site looking for earthquake information, the felt percentages are clearly overestimated. However, since the sampling method was the same for all cases, the relative behavior of different “conditions” should not be impacted.

The plots indicate that, within the general attenuation trend of felt percentage versus distance, it is possible to distinguish the behavior of each "condition". In fact, the curves followed an almost parallel trend beginning from a saturated value of nearly 100% felt near the epicenter to a value approaching 0% at larger distances.

To check the significance of the different behavior among conditions, the Chi squared test was performed on the frequencies of "felt" and "not felt" at distances 30, 75, 140, 180 respectively for Figs. 2a, 2b, 2c, 2d corresponding to percentage values far from saturation. The distributions resulted significantly different for all couples, except for those that are very close each other in Fig. 2 (Tabs. S2, S3, S4, S5, Fig. S3, available in the electronic supplement to this article).

For low magnitude (Fig. 2a) the curves appear to be grouped for "situation" (in sequence from top to bottom for "at rest", "sleeping", and "in motion"), and, inside of each group, ordered by "location" (in sequence from top to bottom for "higher floors", "lower floors", and "outdoors"). For higher magnitude (Fig. 2b,c,d) the "sleeping" curves are near to the "at rest – lower floors" and "at rest – outdoors" ones. The maximum distance reported on the graphs (Fig. 2) corresponds to the distance beyond which the macroseismic "not felt" was generally expected to prevail. Interesting to note is that the different levels reached by the curves at longer distances, in particular for "at rest - higher floors", maintained values of felt percentage of approximately 50%; whereas "in motion – lower floors" were, reasonably, fewer than 10%. The range of magnitude for each plot was quite large, ensuring a large amount of data for each "condition" and distance range. On the other hand, inside each magnitude range felt percentages came from different earthquakes. As an example, in Fig. 2b where we mixed events of magnitude 4 to 4.9 the data came from intensities over a range of one degree. To overwhelm this problem we decided to put together data with respect to its degree of EMS intensity instead of its hypocentral distance.

Using the procedure described by Sbarra et al. (2010), all of the questionnaire answers were statistically analyzed by the procedures implemented on our Internet site www.haisentitoilterremoto.it. As for other web-based questionnaires (Wald et al., 2011), our automated procedure controls the reliability of questionnaires and discharges those that either contain contradictory answers or that exceed 2.5 EMS degrees over the expected intensity based on attenuation laws. Macroseismic intensity for a municipality is assessed by adding the intensity scores associated with the answers for all of the questionnaires and by determining the mode of the score distribution. The system was versatile and allowed us to assess the intensity degree measured using different macroseismic scales, only modifying the intensity scores (associated to each answer) according to the degree definitions. We routinely assigned intensity values for both the MCS and EMS scales. The difference in values between the two scales was quite small. In fact, all of the 12-degree intensity scales were observed to behave in a similar manner, especially regarding low degrees (Murphy and O'Brien, 1977; Musson et al., 2010). Our database of intensity values contained a great quantity of data for low degrees, belonging to both long distances from large earthquakes and short distances from small earthquakes. Low intensity degrees are generally disregarded by traditional macroseismic analysis. As a result main attenuation relationships for Italy are defined for large magnitudes and high intensities (Pasolini et al., 2008). In order to calculate an attenuation relationship as a function of distance and earthquake magnitude applicable to our data, we fit a planar surface using EMS intensity as a dependent variable ($\hat{I}$), whereas the magnitude (M_L) and the decimal logarithm of the kilometric distance from the hypocenter (log R) were independent variables. We only considered the intensities of municipalities having more than five questionnaires. The relationship found to be highly significant was: $\hat{I} = -2.26 \ \log R + 1.08 \ M_L + 2.22$. A similar equation with different coefficients was proposed by Musson (2005b) for data from the United Kingdom. We then associated each questionnaire to the value $\hat{I}$ computed using the corresponding log R and M_L.

As already mentioned, our quantities of "not felt" report are underestimated, thus we evaluated the correcting factors to be multiplied to the not felt number in order to have corrected felt percentages comparable with the values reported in EMS scale description (Grünthal 1998). Considering the municipalities having at least fifty questionnaires, we analyzed the underestimation of not felt report in respect to percentages corresponding to the middle of the ranges for III, IV and V EMS (respectively 92%, 65%, 28%). The mean multiplicative factors obtained are well aligned on a straight line (Fig. S4, available in the electronic supplement to this article) and show that the underestimation is greater for low intensity because the people attention is higher in the areas characterized by heavier effects. We then extrapolated the factors on the base of the least squares fit for all EMS degrees. In detail the corrective factors are 175, 150, 120, 95, 75, 55, 25 respectively for II-III, III, III-IV, IV, IV-V, V and V-VI EMS.

Applying both the attenuation relation and the “not felt” correcting factors, we calculated and plotted the corrected felt percentages grouped by ”condition” with respect to macroseismic intensity (Fig. 3). The corrected felt percentages are comparable to the EMS ones, permitting to evaluate the impact of the “condition” of the observer on earthquake perception. The general parallel trend shown in Fig. 2 was confirmed. The smoother shapes of Fig. 3 benefited from a greater number of data used for calculating each value (Fig. S4, available in the electronic supplement to this article). The sequence of curves maintained the same disposition. Felt percentages calculated for observers “at rest” yielded the highest values, while percentages relative to people “in motion” were the lowest. Sleeping situations were mainly located in the middle. For each “situation” the order of the location, from higher floors 15 through lower floors down to the outdoors, for each degree, was respected for almost all the conditions. In the Figs. 2 and 3, a , line connects points referring to “in motion – outdoors” because we suspected that some of the respondents interpreted this category as meaning inside of a moving vehicle. For this reason the associated percentages were low.

We show in Fig. 4 (tabular data are in Tab. S6, available in the electronic supplement to this article), for the same intensity ranges provided in Fig. 3, the relative proportions of the three vibration levels (weak, moderate, and strong) as reported in the “felt” questionnaires, together with those “not felt” (here referred to as “none”). In this manner, the felt percentages provided in Fig. 3 were split into three categories. The width of the slices represents shaking level percentage on the total responses for each case. From the top to the bottom, pie plot rows correspond to different “conditions” in the same manner as for the curves of Fig. 3. Shaking level percentages indicate that the difference amongst diverse conditions is mainly due to the weak vibration, preferentially felt by observers at rest. On the other hand, the percentage of strong vibrations was less affected by observer conditions.

In order to further analyze the variability of reported shaking at different “conditions”, we applied the Multivariate Correspondence Analysis (MCA). MCA belongs to the ample family of multivariate analysis that includes (principal component analysis, factor analysis, principal coordinates analysis and canonical correlation). They basically aim to reduce the complexity of a multidimensional process, keeping as much as possible the information content of the original data set. In fact, data are normally constituted by a number of samples where, for each one, a defined number of characteristics (variables) are measured. Main objective of the analysis is to reduce the number of original variables (i.e. the characteristics measured for each sample), through the analysis of the mutual correlations, introducing a new variable made with a combination of them. The count of questionnaires reporting a specific vibration level constitute a 8 per 36 data matrix (Tab S6, available in the electronic supplement to this article) in which “conditions” are rows (8 samples) and vibration level for each EMS degree (intermediate degrees included) are columns (a total of 36 variables). MCA is well suited for enumerative data as nominal or ordinal observations (Davis, 1986). The general scheme of the analysis starts from the creation of a symmetric similarity matrix r_{jk} in the form:

$$r_{jk} = \sum_{i=1}^{n} \left(\frac{O_{ij} - E_{ij}}{\sqrt{E_{ij}}} \right) \left(\frac{O_{ik} - E_{ik}}{\sqrt{E_{ik}}} \right)$$

where O_{ij} and E_{ij} are respectively the observed and the expected values for the sample i and variable j (the same is for variable k). O_{ij} is the percentage of reports for a specific condition and vibration level. E_{ij} is the product of the probability to have reports for a specific condition (regardless the vibration level) with the probability to have reports for a vibration level (regardless the condition). Successively eigenvalues and eigenvectors are extracted from the r_{jk} matrix. Each eigenvalue and associated eigenvectors can be represented as principal axis of the so-called factor space. Each eigenvalue has eigenvectors (one for each original variable), they represent the correlation of each original variable with the respective principal axis. The eigenvalue is usually expressed as percentage of variance (also referred as inertia, related to the information content of the data) on the total variance obtained with the sum of all eigenvalues. Following specific transformations, involving eigenvalues and eigenvectors, we obtain, for each original variable, a scaled factor loading value for each factor axis, so we can plot all variables on a factor space. Following a similar procedure we obtain scaled factor loadings for each sample too, and we plot them on the same factor space with the same metrics. Variables, or samples, occupying the same portion of factor space have similar behavior.

In this analysis we, note that two axes of factor space are enough (Fig. 5) to express a sufficiently amount of information, simplifying data interpretation. In fact the first two eigenvalues account the 95.87% of total variance (respectively 65.31% the first and 30.56% the second one). In Fig. 5 two main groups are present: the “not felt” (not at all vibration) close to the “in motion” situation, and the other vibration levels close to “sleeping” and “at rest” situation. The first group shows that people “in motion” often do not feel the earthquake, whereas the latter group is approximately ordered according to the vibration level, from weak to strong. This order is reasonably related to observer’s “condition”. In fact people at rest indoors are better suited to report weak and moderate vibration, whereas people at rest outdoors or sleeping experience moderate and strong shaking. Moreover, while “at rest”, people feel the III EMS as a weak vibration, following the EMS scale, but only if located at higher floors.

To better group the “condition” samples, we applied the cluster analysis on correspondence axis loadings. Cutting the resulting dendrogram (Fig. S6, available in the electronic supplement to this article, and slashed areas in Fig. 5) at similarity threshold 1.0, we observe that samples cluster with respect to “sleeping”, “at rest”, and “in motion”, indicating that vibration perception is first driven by "situation" then by “location”. This analysis statistically confirms the previous consideration about the influence of conditions on earthquake perception. The only exception is the condition “at rest - outdoors” that is slightly nearer to “sleeping” group than to “at rest” one.

Discussion

On the base of our results we deduced the relative influence of “situation” and “location” on earthquake perception. In detail (Figs. 2, 3) the felt percentages for people at rest at higher floors are the highest, especially for long distances, whereas the worst perception occurred when people were in motion, as proved by the correspondence analysis (Fig. 5). Interesting to note is that the vibration felt outdoors at rest was higher than the vibration felt while in motion inside a building regardless of floor level (Figs. 2, 3), confirming that "location" plays a secondary role. For people at rest at lower floors and outdoors the felt percentages were similar. For sleeping people, the felt percentages for low magnitudes were between situation "at rest" and "in motion" and similar to "at rest" for higher magnitudes (Fig. 2). The "in motion - outdoors" curve (dashed line in Fig. 3) was quite different from the others, likely because it was sometimes erroneously associated with being in a moving vehicle. This difference is evidenced by the correspondence and cluster analyses that separate such condition from the others (Fig. 5 and Fig. S6, available in the electronic supplement to this article). In our Internet questionnaire's present form, to exclude any misunderstandings, we added a new answer "in a car" to the question regarding "location".

As previously mentioned, due to the scarce number of people reporting a not felt earthquake, all of the obtained experimental felt percentages are overestimated. In fact, despite the contribution of the group of registered users, the number of not felt reports is not fully representative, as commonly occurs in internet-based macroseismic questionnaires (Boatwright et al., 2012).We applied multiplicative correcting factors, experimentally obtained, to make corrected felt percentages comparable to those reported in EMS scale (Fig. 3, and Fig. S4, available in the electronic supplement to this article).

Following the results presented in Fig. 3, we propose in Tab. 1 the specifications, using both adjectives (most, many, few) and percentages that should be operatively applied to improve the assessment of low intensities. The EMS scale specifies that vibration is less felt outdoors with a difference up to two intensity degrees as compared to indoors. In other words, a shaking felt by many indoors corresponds to intensity IV, while if many feel an earthquake outdoors it corresponds to intensity VI. Instead, on the base of our results, a shaking felt by many at rest at both higher and lower floors correspond to intensity IV, while an earthquake felt by many "at rest - outdoors" correspond to intensity IV-V (Tab. 1). Considering this result currently the intensity assessment, following the criteria of the EMS scale involving people “at rest – outdoors”, are overestimated of 1.5 EMS. Additionally, the outdoor effects described in the macroseismic scales are relatively few, consequently the correct evaluation of the felt percentage in respect to ”situation” is even more important.

For the EMS scale, reference to “situation” is quoted in the description of the intensity III where it is specified that “few people at rest” felt a light trembling. Sleeping people are mentioned in intensity IV where few are awakened. Therefore, in the case of a vibration felt by few people at rest indoor and a shaking that awakens few people there is a relative difference of one degree (Tab 1). Whereas, according to our results, this difference is 0.5 EMS because a few are awakened at III-IV (Tab. 1). The greatest separation (one degree, Fig. 3) was evidenced when comparing the same felt percentage of people “at rest – higher floors” and “in motion – lower floors”, a double difference in respect to different “location” at the same “situation”. A simple way to apply the results evidenced in this study, as a first approximation, is to change only the word “indoors” with “at rest” and the word “outdoors” with “in motion” in the EMS description (Tab. 1, Fig. 3).

As shown, when people were at rest, the difference of felt percentages, in respect to other situation, was mainly due to weak vibration (Figs. 4, 5). Weak vibration was, in fact, most likely to be perceived under optimal situations without any type of disturbance. We can note that the correspondence analysis (Fig. 5) plots weak vibration variables near situation “at rest”. The none vibration variables are plotted near situation “in motion”, except for VI EMS that is far from the others due to the obvious scarcity of people reporting none vibration in this degree. On the other hand, strong vibrations percentages were less influenced by conditions, because strong vibration could always be felt.

In the EMS macroseismic scale the recommended practice was “To discount all reports from observers higher than the fifth floor when assigning intensity” (Grünthal, 1998). However, on the basis of our results, the vibration perceived at higher floors was effectively stronger only if the observers were at rest. By analyzing the database of “haisentitoilterremoto”, quantification of the “floor effect” was previously investigated (Sbarra et al. 2012). For the “floor effect” the authors found that the amplification of macroseismic effects is proportional to both height of the observation floor and earthquake magnitude. The maximum intensity variation between the highest and lowest floors was half a MCS degree. However, these values should be revised for the observer “situation”. In fact, people “at rest” perceive a greater shaking. The complexity of the phenomenon, influenced by several variables, can be studied by analyzing one parameter at a time while fixing the others, as proposed by this paper.

Conclusions

The large amount of experimental data collected for Italian earthquakes of low-medium magnitude allowed the characterization of the effect of observer condition on earthquake perception. Quantification of the relative weight of “situation” and “location" variables is a fundamental step for a correct evaluation of low macroseismic intensity degrees, which are generally assessed by only considering qualitative descriptions.

According to the description of macroseismic scales, the “location” variable has more weight with respect to “situation”. Whereas our results indicated that the “situation” (“at rest”, “in motion”, or “sleeping”) had more influence on earthquake perception. For observation made at rest on higher floors felt percentage was the highest. People in motion had the worst perception. Felt percentage for sleeping situation is, generally, in between those at rest on higher floors and in motion.

Attention should be paid to the macroseismic surveillance of low intensities. In fact, the incorrect sampling of observers can cause a bias in the intensity assessment by more than half a degree.

As a first approximation we propose changigin the word “indoors” with “at rest” and the word “outdoors” with “in motion” in the description of the EMS scale. We detail (Tab. 1) the specifications that should be operatively applied to improve the assessment of low intensities considering both "situation" and "location" of observers. We thus highlight the need to ask about "situation" in macroseismic questionnaire.

Acknowledgments

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Figure captions

Figure 1. Map of earthquakes considered in this study. The Northern and the Southern clusters pertain to the seismic sequences respectively of Emilia (May 2012) and L'Aquila (April 2009).

Figure 2. The percentage of people feeling a quake to total respondents with respect to the hypocentral distance for the specified magnitude ranges. Each symbol corresponds to the percentage calculated by observers as characterized by a specific ”condition”.

Figure 3. Felt percentages corresponding to each EMS intensity degree. Each symbol corresponds to the percentage calculated by observers as characterized by a specific ”condition”. The experimental points are connected with a smooth line only for interpretation. The adjectives reported on ordinate axis correspond to the definitions of quantity according to EMS specifications.

Figure 4. Pie graphs of the vibration level felt by observers for each EMS intensity degree with respect to different “conditions”.

Figure 5. Classification of conditions and vibration levels as resulting from representation of correspondence analysis. Gray squares refer to conditions. Round symbols refer to reported vibration level (none, weak, moderate, strong) at the specified EMS intensity degree (Roman numerals). Tick mark spacing on axes is 0.2. Slashed areas correspond to the condition groups identified by the cluster analysis.

EMS degree	**Description (Grünthal, 1998)**	**Description proposed**
III	“... felt indoors by a few.”	Felt by a few at rest at higher floors (5%) and by very few at rest at lower floors (2%).
IV	“... felt indoors by many and felt outdoors only by very few. A few people are awakened.”	Felt by many at rest at higher floors (33%), by many at rest at lower floors (23%), by few/many at rest outdoor (15%), by a few in motion at higher floors (12%), by few in motion at lower floors (6%). Many people are awakened at higher floors (33%), and at lower floors (18%).
V	“... felt indoors by most, outdoors by few. ... Many sleeping people awake.”	Felt by most at rest at both higher floors (86%) and lower floors (64%), and outdoors (78 %). By many in motion at both higher floors (53%) and lower floors (28%). By a few in motion outdoors (7%). Most people are awakened at both higher floors (77%) and lower floors (82%).
VI	“Felt by most indoors and by many outdoors.”	Felt by all at rest or in motion (100%). All people are awakened (100%).

Table 1. EMS scale description and our corresponding specifications.

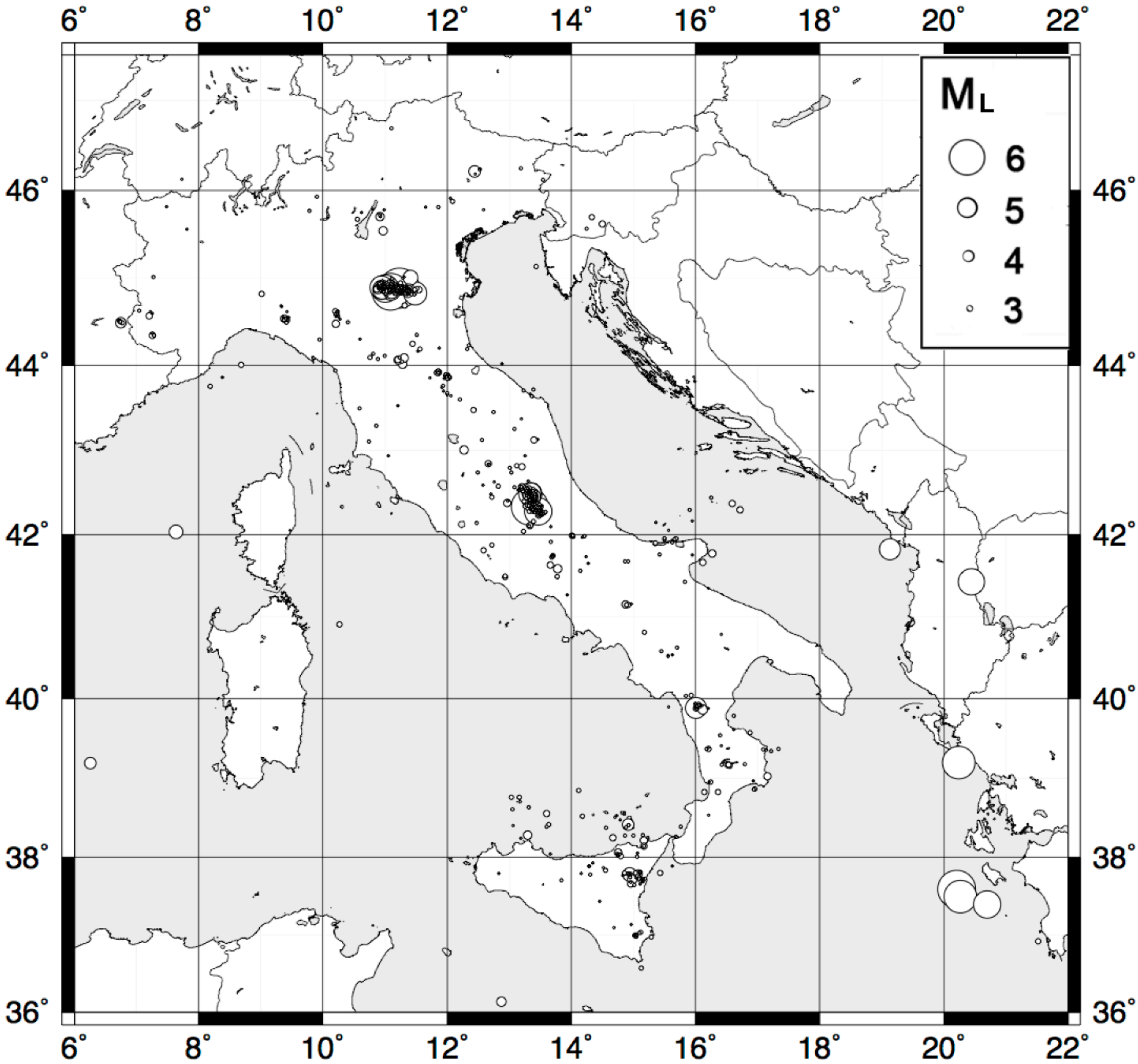


Figure 1

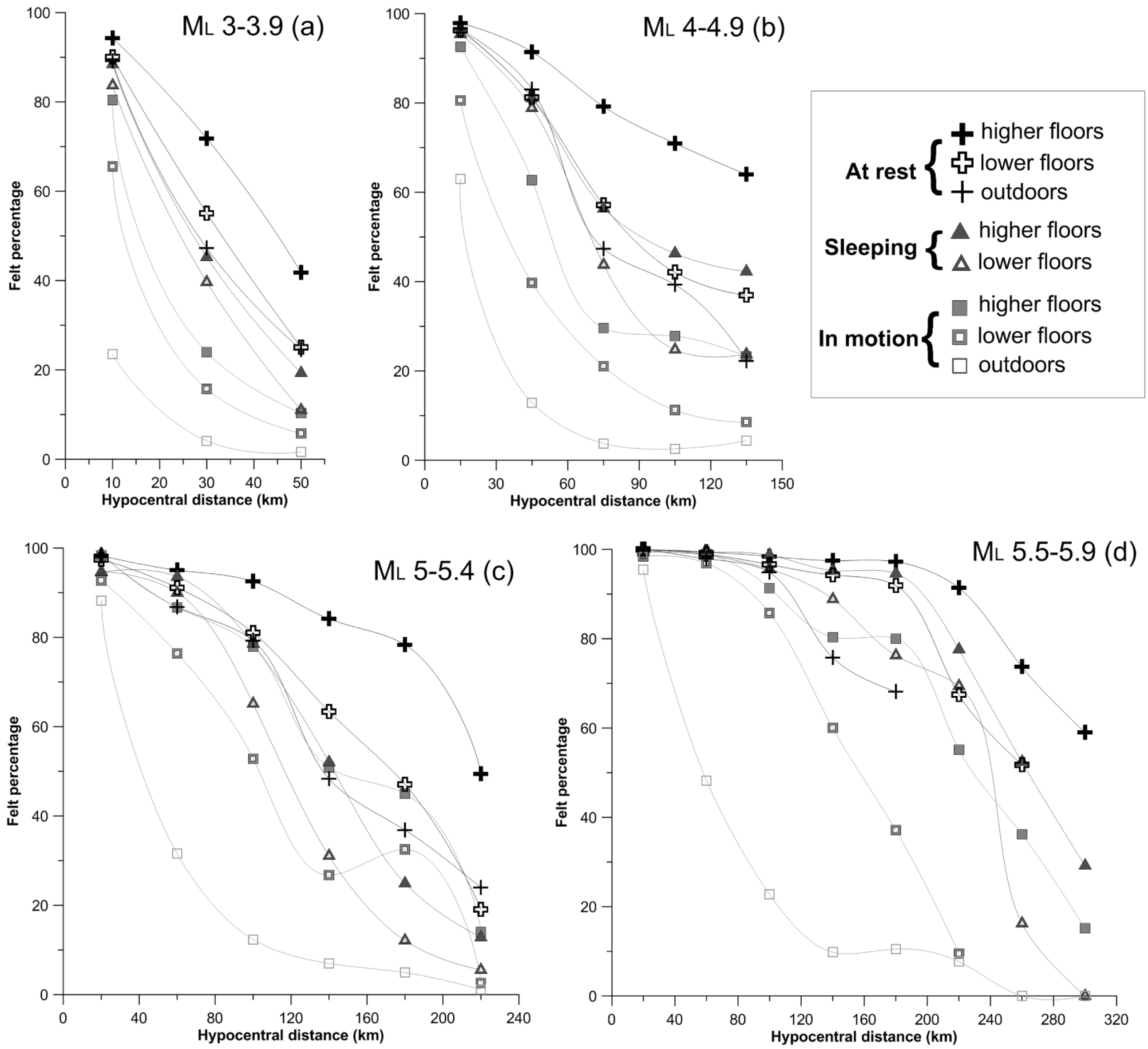
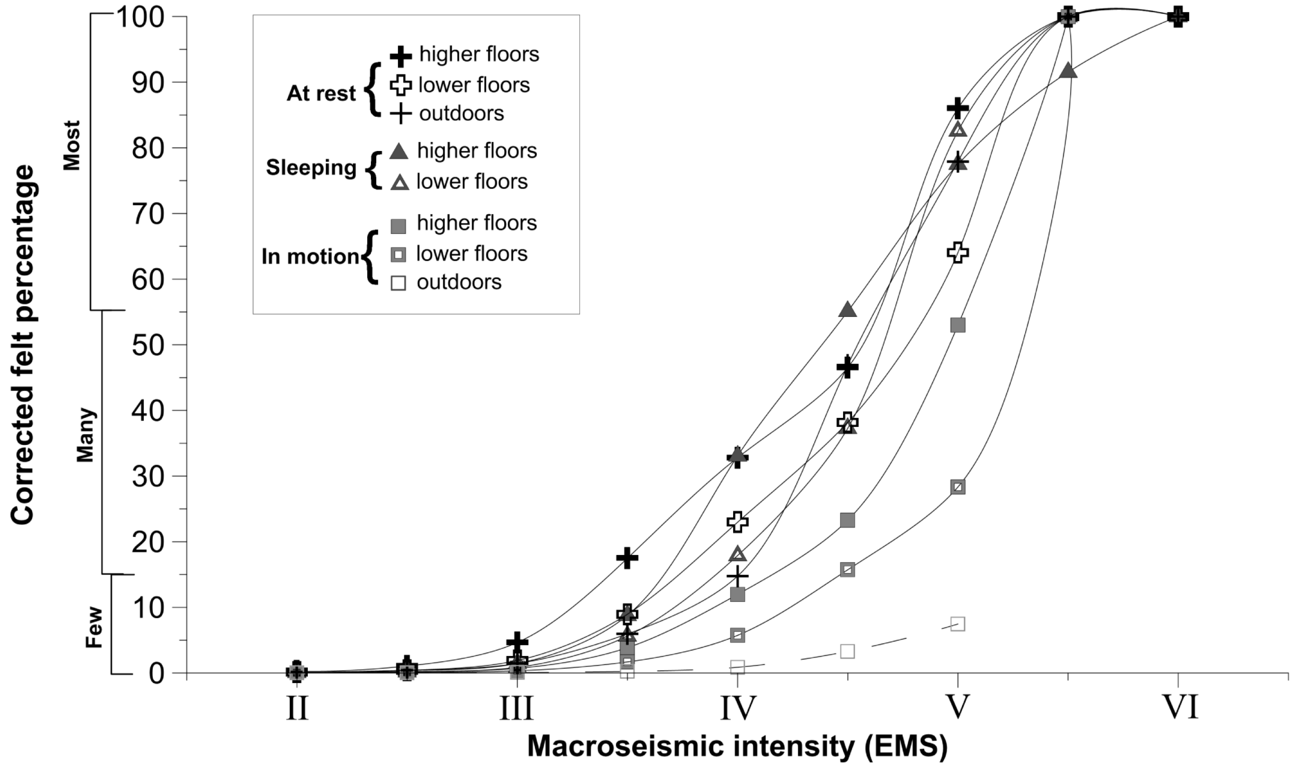

ML 3-3.9 (a)
ML 4-4.9 (b)
ML 5-5.4 (c)
ML 5.5-5.9 (d)
Felt percentage
Hypocentral distance (km)
At rest
higher floors
lower floors
outdoors
Sleeping
higher floors
lower floors
In motion
higher floors
lower floors
outdoors

Figure 2



Corrected felt percentage
Most
Many
Few
100
90
80
70
60
50
40
30
20
10
0
At rest
higher floors
lower floors
outdoors
Sleeping
higher floors
lower floors
In motion
higher floors
lower floors
outdoors
II
III
IV
V
VI
Macroseismic intensity (EMS)

Figure 3

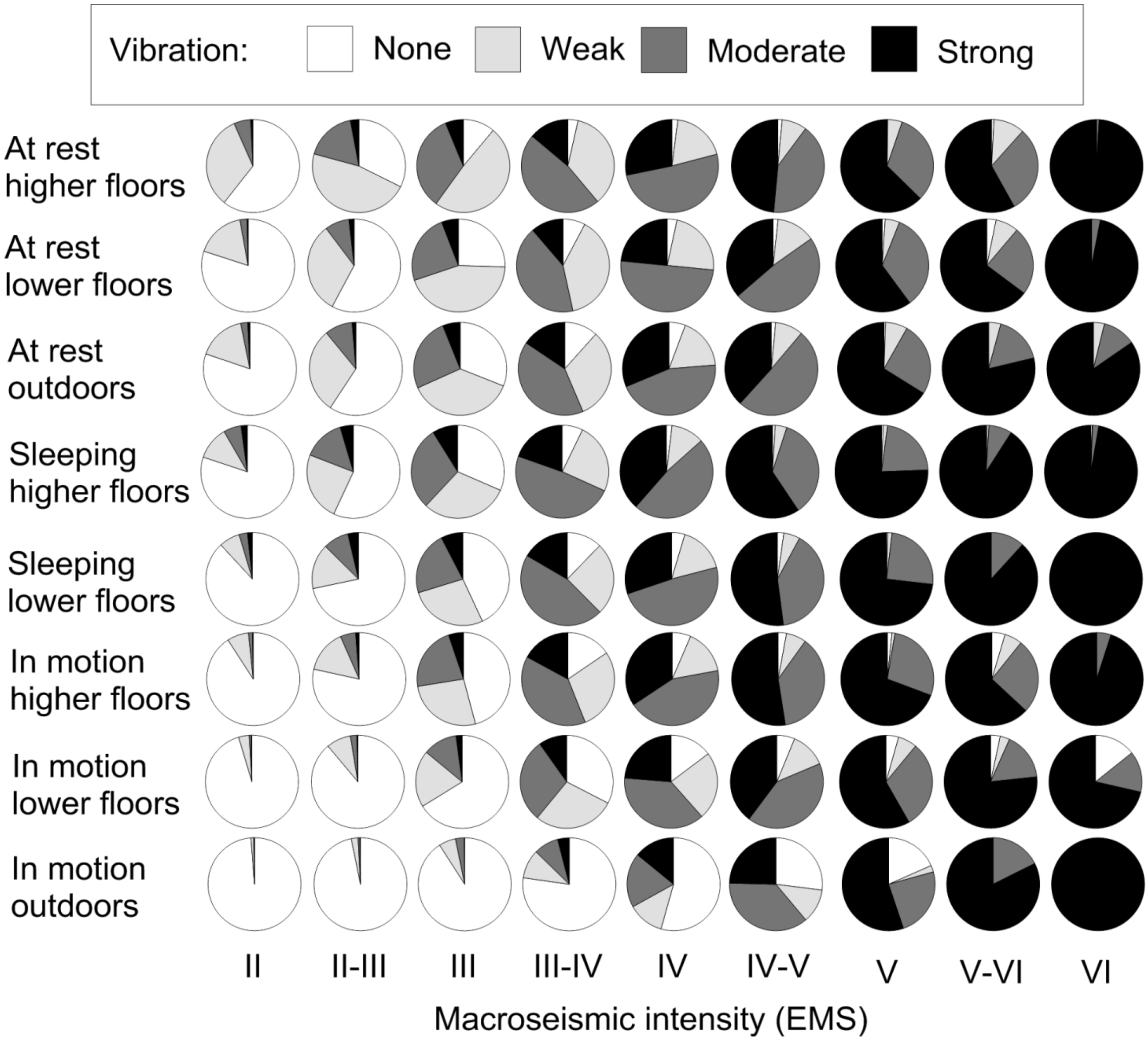

Vibration:
None
Weak
Moderate
Strong
At rest higher floors
At rest lower floors
At rest outdoors
Sleeping higher floors
Sleeping lower floors
In motion higher floors
In motion lower floors
In motion outdoors
II
II-III
III
III-IV
IV
IV-V
V
V-VI
VI
Macroseismic intensity (EMS)

Figure 4

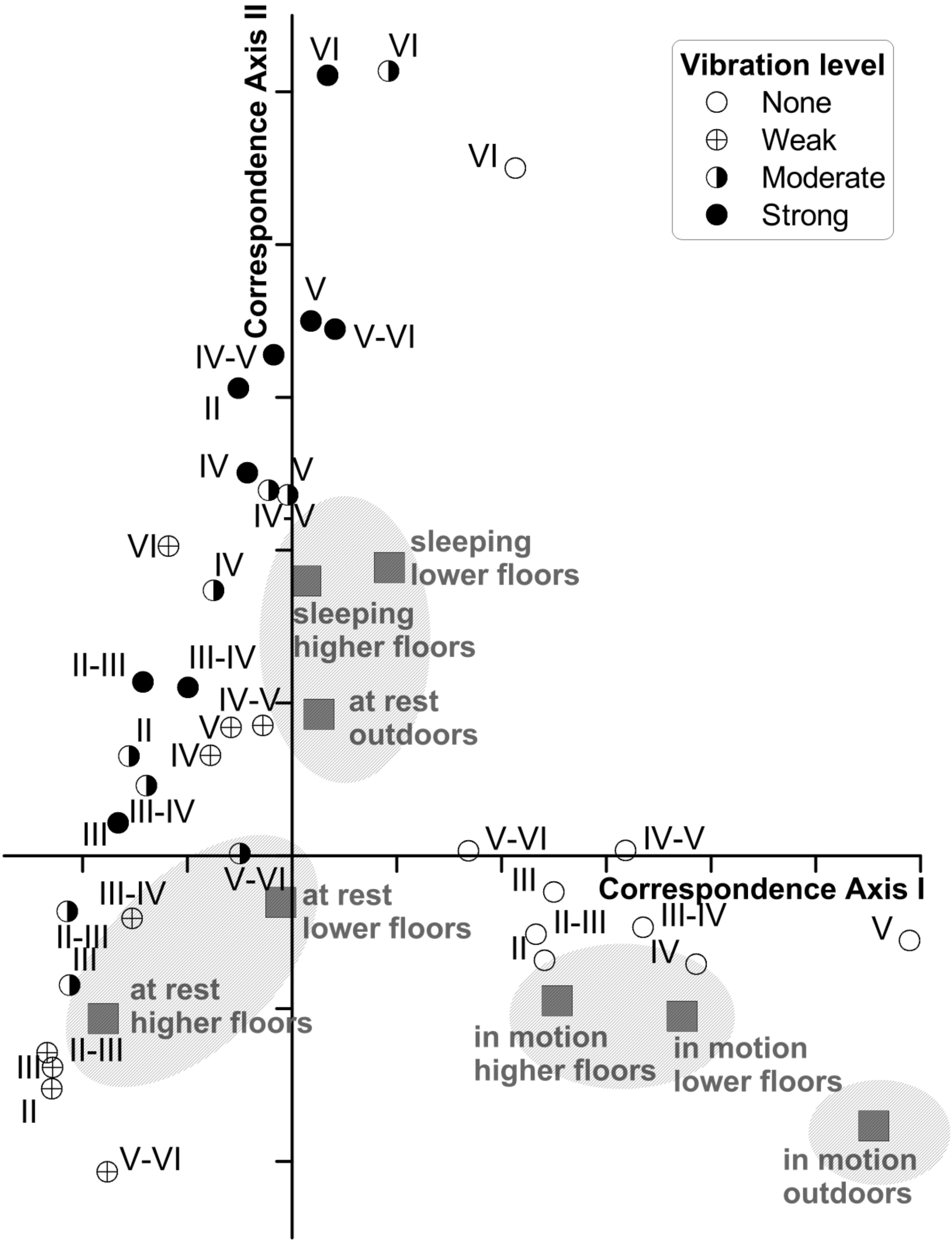

Correspondence Axis II
Correspondence Axis I
Vibration level
None
Weak
Moderate
Strong
VI
VI
VI
V
V-VI
IV-V
II
IV
V
IV-V
VI
IV
sleeping
lower floors
sleeping
higher floors
II-III
III-IV
IV-V
at rest
outdoors
II
V
IV
III-IV
III
V-VI
IV-V
V-VI
at rest
lower floors
III-IV
III
II-III
III-IV
II-III
II
V
III
IV
at rest
higher floors
II-III
III
II
in motion
higher floors
in motion
lower floors
V-VI
in motion
outdoors

Figure 5