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How does an earthquake feel like inside a car?

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Abstract

The analysis of how an earthquake is felt was addressed with the data provided by citizens through a website dedicated to the perception of earthquakes in Italy (www.haisentitoilterremoto.it). The analysis was focused on the perception of earthquakes by observers inside both parked and moving cars. These situations were compared with outdoor ones. The felt percentage of each situation was quantified for epicentral distance ranges and EMS degree. One of the main findings was the greatest sensitivity to shaking for people inside parked cars, due to resonance phenomena of the automobile-observer system. The distribution of the intensity of perception in the car was analyzed as a function of the hypocentral distance and the magnitude of the earthquake. It was possible to define the attenuation trends of these intensities. The comparison of these trends with those of the equations for estimation of response spectral ordinates, allowed us to have an evaluation of the frequency values of the seismic waves that caused the vibrations felt, which were found to be in agreement with the typical frequencies of the car-observer system, as highlighted by independent studies. The results of this analysis show the possibility to include the perception of the earthquake inside a parked and moving car among the diagnostics used in the definition of macroseismic intensity degree of the European Macroseismic Scale (EMS).

Introduction

Research on the effects of earthquakes on people and structures is a fundamental activity for a correct assessment of macroseismic intensity. The aim of this article is to analyze how an earthquake is felt inside a parked or moving vehicle, and how this condition impacts the perception of the earthquake. Is there a greater or lesser perception of ground shaking compared to being outdoors? What might any difference be due to?

Determining whether and to what extent certain conditions (being inside a building or outdoors, while moving, at rest, or sleeping) influence earthquake perception is one of the areas the authors of this article have already researched in the past. In particular, Sbarra et al. (2014) focused on how each condition impacts the observer's perception of ground shaking. However, conditions in an automobile were not contemplated in that article, as there were insufficient data to describe them at the time.

In addition to the perception inside an automobile, this article presents an analysis of data regarding people who felt the earthquake while at rest or in motion outdoors; firstly, to verify that these felt percentages differ from those of people in a parked or moving vehicle, as well as to have a benchmark for comparison with people inside a building (Sbarra et al. 2014).

Another element that will be considered is the attenuation of the percentage of people who feel the earthquake inside an automobile, as a function of distance and magnitude. In fact, in Tosi et al. (2017), different earthquake effects were shown to be attenuated in slightly different ways, similarly to the attenuation of seismic waves of different frequency. It is logical to assume that objects and people are more sensitive, as instruments are, to certain frequencies. This indicates that each effect deemed to be a diagnostic for intensity scales is attenuated like the shaking caused by waves with a particular frequency interval, which might change due to different conditions or situations, such as being inside an automobile, for example.

The perception of earthquake-induced shaking inside an automobile is not mentioned in the European Macroseismic Scale (EMS, Grünthal, 1998), nor in the Mercalli Cancani Sieberg Scale (MCS, Sieberg, 1930). Nevertheless, in many online macroseismic questionnaires (see Radziminovich et al., 2014; Van Noten et al., 2017), observers are asked to report their location at the time of the earthquake, and the choices listed usually include being in an automobile.

Conversely, earthquake perception inside a vehicle is deemed to be a diagnostic effect in the Modified Mercalli Intensity macroseismic scale (MMI, Wood and Neumann, 1931; Stover and Coffman, 1993; Musson and Cecić, 2012) and in the scale published by the Japanese Meteorological Agency (JMA; see Data and Resources, Musson and Cecić, 2012).

Some authors have studied the effect of an earthquake on motor vehicle driving, by analyzing questionnaire responses reported following single major earthquakes in Japan (Kawashima et al.,1989; Maruyama and Yamazaki, 2006). The study conducted by Kawashima et al. (1989) highlighted that, for medium-to-high intensities, there is a difference in the percentage of people who perceive an earthquake inside a parked or moving vehicle, while Maruyama and Yamazaki (2006) also include low intensities in their analysis of the perception inside a moving car. The aim of the present study is precisely to characterize and quantify the percentage of people who feel the earthquake inside a parked vehicle and inside a moving vehicle at intensities lower than 6 EMS.

Data

Thanks to crowdsourcing data and citizen science, it is possible to reach out to and engage a large number of people to gather macroseismic data on earthquake effects. This also allows for the analysis of low-intensity data for low-magnitude earthquakes or the far-field of strong earthquakes. In Italy, the National Institute of Geophysics and Volcanology (INGV) is running the project called “Did you feel the earthquake?” (“Hai Sentito il Terremoto”, HSIT), through the collection of responses to a web-based questionnaire on how earthquakes were felt in Italy.

The macroseismic questionnaire (see Data and Resources) is completed both by volunteers and a group of 30,000 registered users who are asked to fill in the questionnaire via e-mail immediately after a seismic event. We know that, despite the registered user group, the number of not-felt questionnaires is underestimated in respect to the whole population, but, for the purpose of this analysis, we assumed that the willingness to fill in the questionnaire was not influenced by the observer's condition, as it is reasonable that these two factors are mutually independent.

The HSIT macroseismic questionnaire includes a question to determine the observer's location during the shaking caused by the earthquake. In 2013, the answer "inside a vehicle" was added to the choices for this question in addition to the options "inside a building" or "outdoors". For this reason, the time interval of the analyzed questionnaires ranges from January 2013 to December 2019. Moreover, we ask in another question whether the observer was at rest or in motion (Tosi et al., 2015). The analysis covers 7969 macroseismic questionnaires from the HSIT macroseismic questionnaire database (see Data and Resources), where respondents were in a moving vehicle at the time of the earthquake; 947 where respondents were in a parked vehicle; 3653 where respondents were at rest outdoors; and 15801 where respondents were in motion outdoors. The questionnaires refer to 3929 earthquakes, which occurred in Italy, or in neighboring countries, at a depth $\leq$ 35km, with a magnitude ranging between 1.8 and 6.8 (ISIDe preferred magnitude; see Data and Resources). For each earthquake, only the questionnaires from municipalities for which at least three reports were submitted have been analyzed.

Feeling an earthquake in a vehicle and outdoors

The percentage of people inside a parked or moving vehicle who felt the earthquake shaking was analyzed as a function of the epicentral distance (Fig. 1) for different magnitude classes. The magnitude intervals considered (ISIDe preferred magnitude; see Data and Resources) were 3-3.9 (Fig. 1a), 4-4.9 (Fig. 1b), 5-5.9 (Fig. 1c). Magnitude classes greater than 5.9 and less than 3 are not shown, as the number of points is not statistically significant. Every distance window is 40 km wide, in order to have sufficient data to obtain a significant result on the percentage trends for the examined conditions. The felt percentage was calculated and placed at the center of the window itself. Each value is labelled with the number of reports used and is shown with its standard error bar, calculated by applying the bootstrap method (Fig. 1, a-c). This well-proven statistical method aims to assign accuracy measures to sample estimates, through the use of random sampling with replacement (Efron and Tibshirani, 1993). Sampling was performed for this analysis 1000 times, each time the felt percentage value was recalculated. The bootstrap estimate of the standard error is the standard deviation of the replications of the percentages. The standard error depends on the number of original points and the consistency of responses.

Generally, the error bar shows that percentages calculated for people in parked or moving vehicles are very separate (Fig. 1). The graphs indicate that there is quite a different perception of earthquake-induced shaking inside parked or moving vehicles, as would appear logical. The same graphs also show the percentages for people outdoors, either at rest or in motion. Furthermore, in Fig. 1, the percentages for the four separate conditions are significantly distinct, for the most part, and the difference is due more to the observer’s situation (at rest or in motion) than his/her location (outdoors or in an automobile). It is worth noting in Fig. 1, that when one is still, one has a clearer perception of the earthquake inside an automobile, as opposed to outside. This difference in perception is considerable with a magnitude greater than 4, except for earthquakes with a higher magnitude felt near the epicenter, where the opposite occurs (Fig. 1c at a distance less than 40 km).

To understand the reasons for this phenomenon, data regarding the two situations were further analyzed using the Tosi et al. (2017) method, that compares the attenuation of a macroseismic effect with the attenuation of the maximum horizontal response at different frequencies of the ground motion. In particular, this method considers the occurrence, related to the number of observers, of a specified macroseismic effect (E) and its attenuation, as a function of the logarithm of hypocentral distance (R) and magnitude (M), approximated by a regression curve with the functional form of Eq. (1).

$$E = a_1 + a_2 M + a_3 logR \qquad (1).$$

The ratio of the coefficients for hypocentral distance and magnitude ($-a_3/a_2$) defines the parameter S, whose values may be compared with those resulting from the attenuation of horizontal response spectra, to have an indication of the oscillation frequencies which are the major cause of the examined effect. Applying this type of analysis to the two situations considered has required some modifications. First of all, the dataset used for the elaboration of this figure is different from that described in the "data" section because it is based on the method proposed in Tosi et al. (2017). In particular, we used a larger data sample because the selection that excluded the questionnaires for which there were less than 3 responses per municipality was not made. Then, the method by Tosi et al. (2017) has been slightly modified to be applied to a smaller number of data. Since for a given constant occurrence E, parameter S also represents the angular coefficient of the line:

$$M = S\ logR + c, \quad (2)$$

the data for individual observers who did (1) or did not (0) feel the earthquake were chosen for processing (Fig. 2), for a more solid determination. The calculation of the discriminating line between values 0 and 1 in the $logR - M$ space, if it exceeds the statistical significance threshold, represents the trend of Eq. (2) for occurrence $E = 0.5$. The discriminating lines for the examined cases (Table 1) differ from one another and are both significant, as the values for probability p associated with the Fisher test F are very low ($p < 0.0001$). After having calculated the parameter S for the two examined cases, it is possible to estimate the frequency response of observers in the two conditions as if they were harmonic oscillators (Fig. 3). In fact, through the comparison with the values of parameter S resulting in the empirical equations for prediction of displacement response spectral ordinates (Cauzzi and Faccioli, 2008), it is possible to find the corresponding period for which the effect is maximum. It appears from Figure 3 that the parameter S for people who feel an earthquake while at rest outdoors (S=2.813) corresponds to a period of 0.2s (5Hz frequency), while parameter S for parked automobile occupants (S=2.276) corresponds to a longer period (0.4s, 2.5Hz frequency). The values obtained are reasonable, since the resonance frequency of a person standing is generally estimated to be around 5Hz (Valentini, 2004), whereas for the human - soft automotive seat combined system it was estimated to be around 2.5-3Hz (Wu et al., 1999). A similar frequency (2-3Hz) was also reported by Kawashima et al. (1989) for the resonance of the vertical vibration of the human body combined with the suspensions and tires of a vehicle. The generally lower attenuation rate of long-period seismic waves explains why one feels medium-high magnitude earthquakes in parked cars more distinctly than when standing outdoors, particularly when the epicentral distance is greater than 40 km. While the opposite occurs for shorter distances where higher frequencies prevail.

Figure 3 shows even S values for other diagnostic effects (Tosi et al., 2017), evidencing the generally lower frequency associated with the effects on objects in respect to the effect on people, that is observers at rest outdoors, in a parked car or indoor who notice the earthquake. People at rest outdoors, in particular, feel the highest frequency shaking, while observers inside a parked car feel the shaking frequency of earthquakes similarly to those who are at rest or in motion indoors.

It was not possible to perform the same analysis for people in a moving vehicle, as there were too few observers who reported feeling the ground shaking in this situation.

European Macroseismic Scale Evaluations

Ground shaking can be perceived quite clearly in a parked automobile, and the percentage of people who felt the earthquake shows a consistent trend as a function of hypocentral distance and magnitude (Fig. 2). Clearly, if the vehicle is moving, only the stronger shaking will be recognized as an earthquake. Although a detailed analysis was not possible with the few data available, an attenuation of the percentage values was observed with distance, particularly near the epicenter of higher-magnitude earthquakes (Fig. 1c). Hence, earthquake perception in a vehicle may be used as a diagnostic of macroseismic intensity. In particular, it was considered for inclusion in the description of the EMS scale**.** For the quantification to be useful for macroseismic purposes, an analysis was performed on the perception of intensity degrees from 2 to 5.5 EMS for people in a parked vehicle, in a moving vehicle, at rest outdoors and in motion outdoors, as a function of the municipal macroseismic intensity reported in the HSIT database (see Data and Resources). The felt percentages in the different intensity degrees, combining data of earthquakes regardless of their magnitude, are shown in Figure 4a. In the graphs in Figure 1, the felt percentages for those who are in motion outdoors are higher than those who are in a moving car, with the difference increasing with rising intensity. We tested these percentages comparing the HSIT EMS intensity of a municipality with the intensity assessed by using only the felt percentages of observers inside a vehicle. For this purpose, we needed a sufficient number of questionnaires filled in by observers inside a vehicle and we found a suitable case for the earthquake of central Italy 26 October 2016 17.10 UTC (Mw 5.4). There were 861 questionnaires from the city of Rome, through which a municipal intensity of 3.5 EMS was assessed. There were also 66 questionnaires filled in by observers inside a car, 12 of which were inside a parked car, and 54 inside a moving car. The felt percentages of these last resulted to be respectively, 83% and 6% in agreement, according to the results shown in Figure 4a, with 3.5 EMS.

The percentages shown in Figure 4a are not directly comparable with the qualitative indications listed on the macroseismic scales because they are referred to a subsample of the population that is formed by citizens who filled in the questionnaire. In fact, the descriptions of the diagnostic effects usually indicate a portion based on the total number of people (“felt” and “not felt”). However, it is worth considering that the “not felt” sample is often underestimated compared to the real population sample. It would therefore be advisable to correct the number of received "not felt" by multiplying it by a specific coefficient, though it is very difficult to estimate it correctly because it varies, for example, according to the media coverage and therefore to the attention given to each earthquake. The issue of underestimating the “not felt” sample is common to all online macroseismic questionnaires (Mak and Schorlemmer, 2016; Boatwright and Phillips, 2017, Quitoriano and Wald, 2020), hence, it would also be advisable to routinely recalibrate the felt percentages for every online system. In the HSIT system, the problem does not even seem to be entirely resolved by including the registered users entered from 2009 onwards, who are asked to respond even if they do not feel the earthquake. Nevertheless, the number of registered users has grown over time and is currently more than 30,000, so the problem of underestimation is decreasing with time. In Sbarra et al. (2014) corrective parameters were calculated to correct the percentages obtained from the web-questionnaires. These correction factors were also applied to this dataset (Fig. 4b) to reproduce the ideal percentages with respect to the whole population and to suggest an operative addition to EMS scale. As an example, at intensity 4 EMS, the earthquake is felt by a few (8%) in a parked vehicle and is not felt in a moving vehicle. Only at 5 EMS, the earthquake is felt by very few (3%) in a moving vehicle. It is interesting to note that for intensity 4-5 EMS, the earthquake is felt by many in a parked vehicle (56%), and the percentage of people who felt the shaking increases a lot if compared to 4 EMS. Furthermore, at intensity 4-5 EMS, the percentage deviates quite a lot from the at-rest outdoor condition (21%).

Comparison with the other scales and among conditions

In the past, the perception of shaking inside an automobile was already used as a diagnostic effect to build up the MMI scale (Wood and Neumann, 1931; Stover and Coffman, 1993; Musson and Cecić, 2012). In the first version of the scale, this diagnostic effect is found in the descriptions of 4 MMI "Rocked standing motor cars noticeably", 5 MMI "felt moderately by people in moving vehicles", 7 MMI "noticed by persons driving motor cars" and 8 MMI "disturbed persons driving motor cars". Subsequently, Stover and Coffman (1993) suggested removing the perception of earthquake-induced shaking inside a vehicle from the upper intensity levels of the scale, as they considered it more appropriate to estimate the intensity solely on the basis of damage to the building.

This diagnostic is also found in the JMA scale, and the following conversion of JMA intensity levels 4 to 6 according to Musson et al. (2010) and Musson and Cecić (2012) may be used to compare this scale with the EMS scale: 4, 5 and 6 JMA correspond to 5, 6 and 7 EMS, respectively. It is also worth noting that the EMS, MCS, MMI and MSK macroseismic scales are very similar to one another for intensity less than 6 (Molin, 1995; Musson et al, 2010).

In the descriptions of 4 JMA (5 EMS), there is a reference to the diagnostic "people driving automobiles notice the tremor". Some Japanese authors focused on the analysis of earthquake perception inside a vehicle for medium-to-high intensity, to assess the effects an earthquake may have on driving. For example, the study by Kawashima et al. (1989) shows different felt percentages for observers in a parked and a moving vehicle. In particular, for the Chiba-ken-Oki earthquake on December 17, 1987, M= 6.7, in a region where the estimated intensity is 5 JMA (6 EMS), the percentage of people noticing the earthquake is 96% for those who were in a moving vehicle and 100% for those in a parked vehicle. In another study, Maruyama and Yamazaki, (2006) showed that for JMA 4 (5 EMS) 53% of automobile drivers feel the vibration of the earthquake inside a moving car and for JMA 5 the relative percentage is 68%. All these percentages, based on a sample of respondents and therefore are values not corrected to represent the whole population, are quite similar to ours (Fig. 4a). We do not have data for EMS 6, but these values are in good agreement with the trend of our percentages for lower intensities.

As shown in Figure 4b, different conditions have an appreciable impact on macroseismic intensity estimation. A felt percentage of about 10% is reached at 4 EMS for those who are still (at rest outdoors or in a parked car), at 4-5 for those who are in motion outdoors, and probably at 6 (as the trend suggests) for those in a moving vehicle; thus, between one condition and another there is a difference of 2 EMS degrees. Also with a 20% felt percentage, the variation range is about 2 EMS degrees, corresponding to 4-5 EMS for those who are still, 5-6 EMS for those who are moving outdoors and probably 6-7 for those in a moving car. This difference may be even greater when considering also the conditions already analyzed in Sbarra et al. (2014), in other words, being at rest or moving inside a building. Therefore, the macroseismic questionnaire must necessarily ask about the place and state of the observer, for a more accurate intensity evaluation. In fact, it is important to distinguish between the conditions that may considerably impact macroseismic intensity evaluation.

As already observed in Sbarra et al., 2014, a comparison with other conditions shows that slight shaking is felt more by observers at rest, and the fact of being at rest or in motion has a greater impact than location (inside a building, outdoors or in an automobile) on the ability to feel the earthquake, for intensities less than 6 EMS. Moreover, thanks to the resonance effect, the observer is in a more favorable condition to feel the earthquake shaking when inside an automobile at rest if compared to being outdoors.

Not only is it essential to include a question on the observer's condition, but as many choices as possible must be specified among the answers to avoid any misunderstandings that may result in inaccurate data.

Conclusions

The results obtained show that the data submitted by citizens through the online questionnaire on earthquake perception are sufficiently accurate in illustrating the differences between the situations, and in how sensitivity to earthquake perception may vary in the intensity range from 2 to 6 EMS. This concept was already highlighted by Sbarra et al. (2014) for observers located inside a building or outdoors, and in situations at rest or in motion, while in this study the perception of the earthquake was analyzed for observers inside an automobile. In particular, the discriminant line between observers who did or did not feel the earthquake has shown that the sensitivity to slight shaking of observers in a parked car is due to the resonance of the automobile-observer system. For this reason, especially in far-field areas, one feels medium-high magnitude earthquakes in a parked car better than when at rest outdoors, as the oscillation period associated with the first condition is longer than the second one and the attenuation rate of the low-frequency seismic waves is lower.

The importance of asking for information about the location and situation of the observer, in macroseismic questionnaires, was once again stressed as in Sbarra et al. (2014), as different conditions affect the evaluation of macroseismic intensity.

The HSIT system does not presently use the questionnaires completed by observers who were inside an automobile at the time of the earthquake in order to calculate EMS macroseismic intensities. Whereas, the quantification of the felt percentages performed in this study (Fig. 4) allow for consideration of these particular conditions and increase the data used for intensity calculation. In particular, for the implementation in HSIT procedures, we will apply these percentages to produce a score matrix, as described in Tosi et al. (2015), in order to probabilistically associate each questionnaire answer to an intensity level.

The results shown herein highlight, yet again, the importance of accurately reporting both observer location and situation, as they can substantially impact macroseismic intensity evaluation. Data on observer conditions, including being inside an automobile, might even be collected by means of image-based questionnaires (Sira, 2015; Bossu et al., 2016; Goded et al., 2017), as they could be clearly illustrated through easy-to-understand pictures for citizens.

Data and Resources

The parameters of the earthquakes were obtained from the INGV earthquake catalogue (ISIDe working group 2016, version 1.0, https://doi.org/10.13127/ISIDe) available from http://cnt.rm.ingv.it/iside (last accessed September 2020).

Macroseismic data used in this article are elaborated and showed in maps or graphics on the Hai Sentito Il Terremoto web site available from https://www.hsit.it/ (last accessed September 2020) citable as: Tosi, P., V. De Rubeis, P. Sbarra, and D. Sorrentino (2007), Hai Sentito Il Terremoto (HSIT) https://doi.org/10.13127/HSIT

HSIT intensity database is available from https://doi.org/10.13127/HSIT/I.1 (last accessed September 2020) and citable as: De Rubeis, V., P. Sbarra, P. Tosi, and D. Sorrentino (2019), Hai Sentito Il Terremoto (HSIT) - Macroseismic intensity database 2007-2018, version 1, doi: 10.13127/HSIT/I.1.

HSIT questionnaire database is available from https://doi.org/10.13127/HSIT/Q.1 (last accessed September 2020) and citable as: Sbarra, P., P. Tosi, V. De Rubeis and D. Sorrentino (2019), Hai Sentito Il Terremoto (HSIT) - Macroseismic questionnaire database 2007-2018, version 1, doi: 10.13127/HSIT/Q.1.

JMA scale is available in Japanese from http://www.jma.go.jp/jma/kishou/know/shindo/index.html (last accessed September 2020).

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Table 1. Discriminating lines of observers who did (1) or did not (0) feel the earthquake as a function of hypocentral distance and magnitude.

	Number of observers	Discriminating line	F Fisher
Observers at rest outdoors	5609	$M = 2.813\ logR - 0.960$	994.44
Observers inside a parked car	1176	$M = 2.276\ logR + 0.205$	281.09

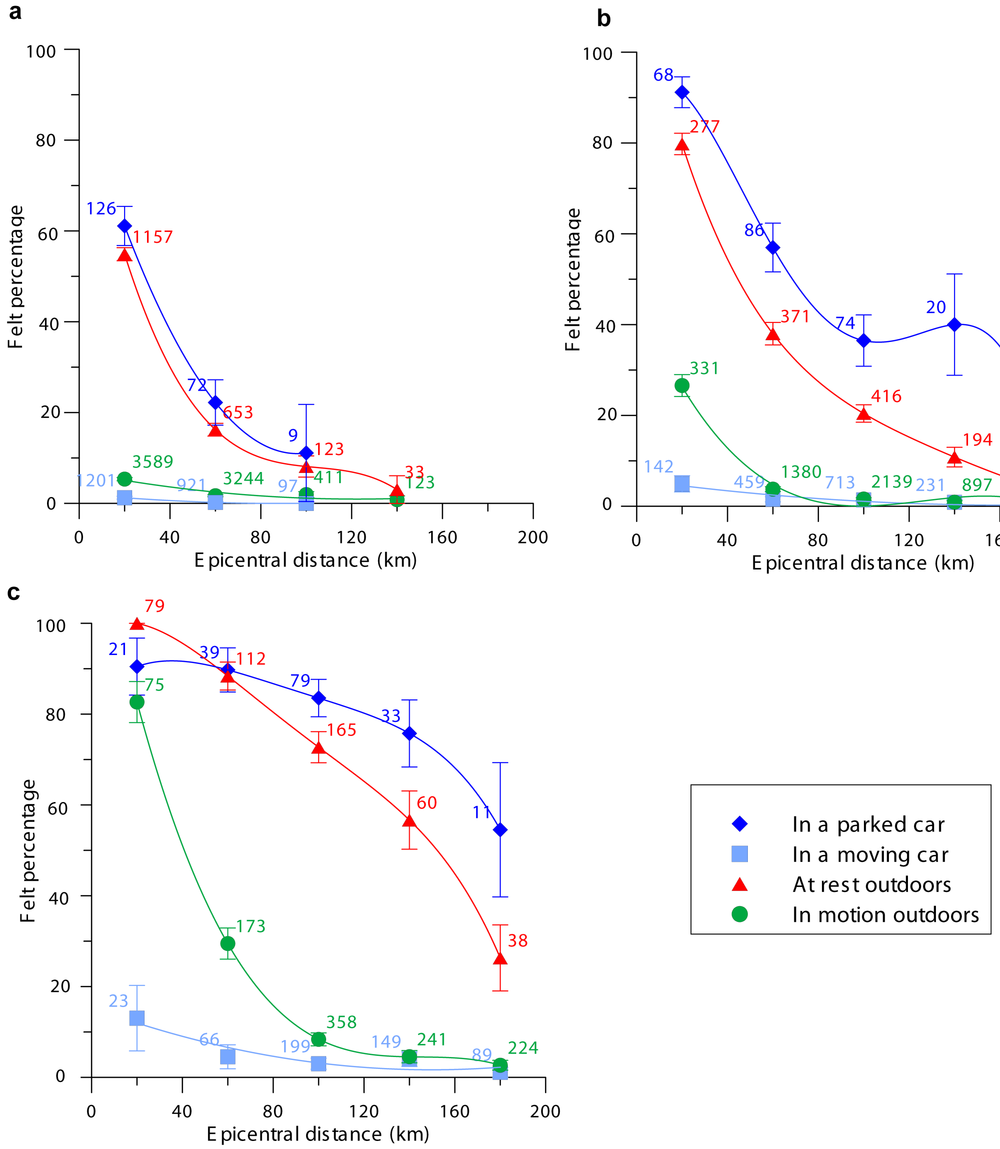

Figure 1. Percentage of people who felt the earthquake, out of the total number of questionnaires for each condition (number indicated next to each point), as a function of epicentral distance for the following magnitude ranges: a) 3 - 3.9; b) 4 - 4.9; c) 5 - 5.9. Each symbol corresponds to the percentage for an observer in a specified condition. Experimental points are connected by an interpolation curve solely for interpretation purposes. For each point, the error bar is calculated using the bootstrap method.

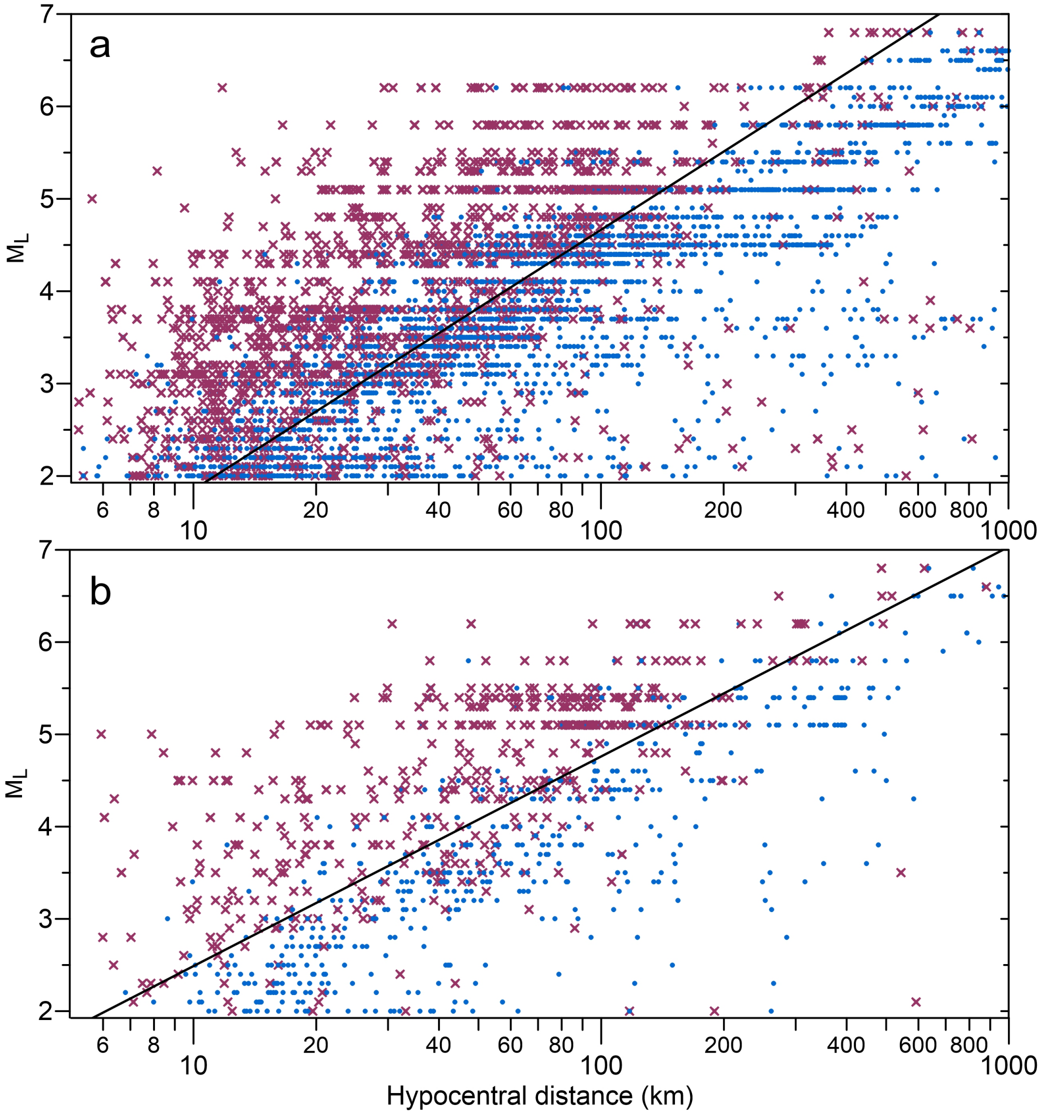

Figure 2. Graph of observers who did (crosses) or did not (dots) feel the earthquake. The black line is the discriminating line. a) Observers at rest outdoors. b) Observers inside a parked car.

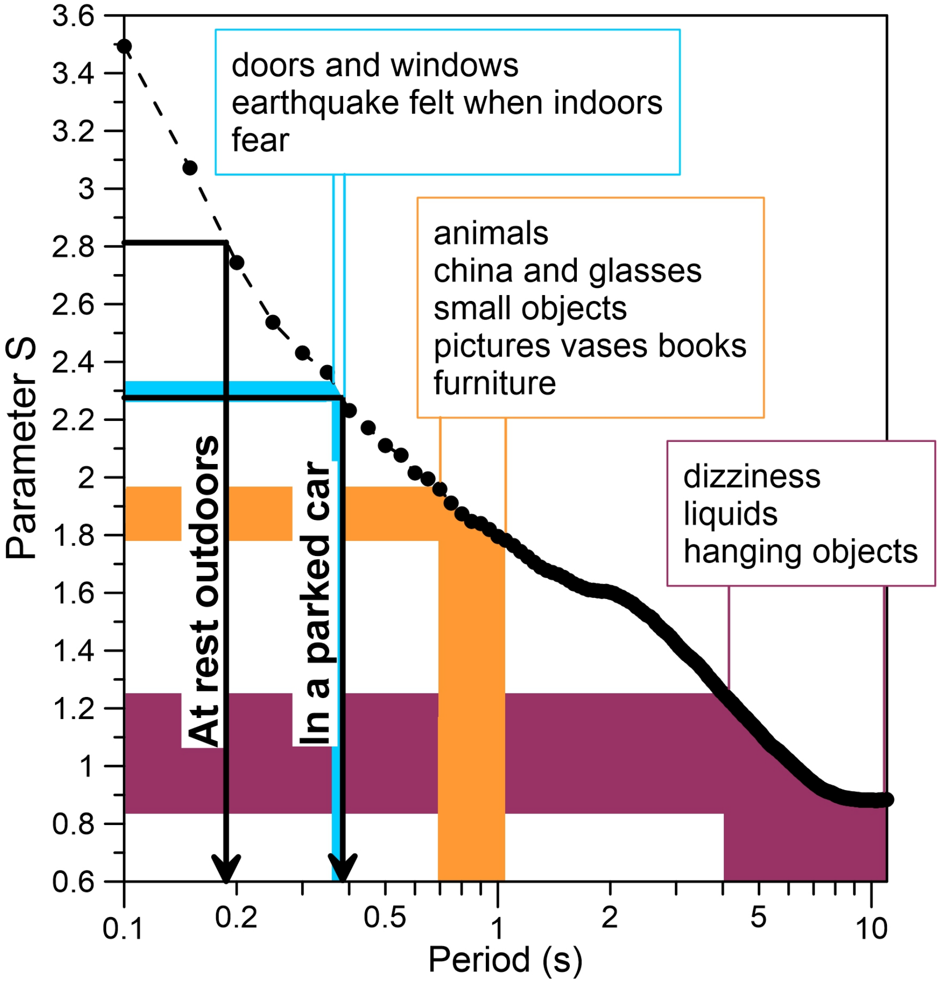

Figure 3. Values of the parameter S (ratio of the coefficients for hypocentral distance and magnitude in the attenuation function, black horizontal lines) computed for observers who felt the earthquake respectively at rest outdoors and in a parked car. The S values are compared with values obtained (Tosi et al., 2017) for 5%-damped horizontal response spectra of displacement (Cauzzi and Faccioli 2008, black dots joined by a dashed line). The black arrows show the corresponding periods for the observers in the two considered conditions. Horizontal stripes mark S experimental values found for the specified macroseismic effects (Tosi et al., 2017) and the corresponding vertical stripes mark the specific period range of resonance.

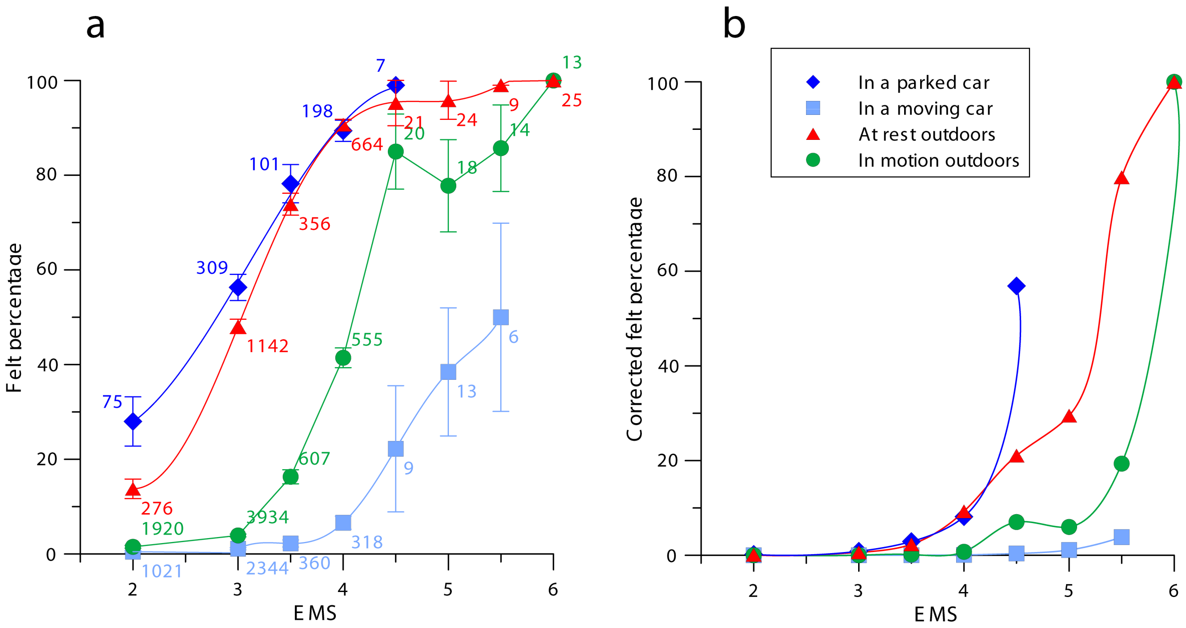

Figure 4. a) Percentage of people who felt the earthquake, out of the total number of questionnaires for each condition (number indicated next to each point), as a function of intensity, from 2 to 6 EMS. Each symbol corresponds to the percentage for an observer in a specified condition. Experimental points are connected by an interpolation curve solely for interpretation purposes. For each point, the error bar is calculated using the bootstrap method. b) Felt percentages shown in a) after the correction for the underestimation of not-felt.