Bulletin of Earthquake Engineering (2024) 22:4245–4263
https://doi.org/10.1007/s10518-024-01921-0

REVIEW ARTICLE

A theoretical comparison among macroseismic scales used in Italy

Gianfranco Vannucci[1] · Barbara Lolli[1] · Paolo Gasperini[1,2]

Received: 20 September 2023 / Accepted: 15 April 2024 / Published online: 17 June 2024
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Abstract

In a recent work, we evidenced some empirical discrepancies between the macroseismic intensity estimates in Italy in the last decade with respect to those made previously. A possible reason might be the progressive adoption by Italian researchers of the European Macroseismic Scale (EMS) in place of the Mercalli Cancani Sieberg (MCS) scale mostly used up to 2009. In theory, in modern settlements where reinforced concrete (RC) buildings are increasingly replacing those in masonry, EMS should overestimate MCS because the former accounts for the lower vulnerability of RC whereas the latter does not because RC buildings were not considered at all by the MCS scale since they were almost absent at the time (1912–1932) when it was compiled by Sieberg. However, such theoretical inference is contradicted by the empirical evidence that, on average, MCS intensities really estimated in Italy over the past decade slightly overestimate EMS and not vice versa as it should be. A possible explanation is that the EMS scale had not been well calibrated to reproduce the MCS, as its authors intended to do. Another possible reason for the discrepancies between the last decade and the previous ones might be that the MCS scale applied today is not the same as that defined by Sieberg at the beginning of the twentieth century. In order to better understand the possible causes of such discrepancies, we present here a formal comparison between the definitions of the different degrees of such macroseismic scales. After such analysis, we might argue that another possible reason for the observed discrepancy may come from the inaccurate assessment of building vulnerability when assessing the EMS intensity.

Keywords Macroseismic scales · Macroseismic intensity · Building vulnerability

✉ Gianfranco Vannucci
gianfranco.vannucci@ingv.it

Barbara Lolli
barbara.lolli@ingv.it

Paolo Gasperini
paolo.gasperini@unibo.it

1 Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Viale Berti Pichat, 6/2, 40127 Bologna, Italy

2 Dipartimento di Fisica e Astronomia, Alma Mater Studiorum, Università di Bologna, Viale Berti Pichat, 8, 40127 Bologna, Italy

1 Introduction

Vannucci et al. (2021), by comparison with instrumental magnitudes computed in Italy since 2010 by the BOXER computer code (Gasperini et al. 1999, 2010), argued that the macroseismic intensities are apparently lower with respect to those computed for previous earthquakes. We report in Fig. 1 an updated version of their Fig. 1, for the interval 1965–2019 when the instrumental magnitudes were most reliable because they were computed using well-calibrated electromagnetic seismometers rather than using mechanical ones mostly used up to about the beginning of the 1960s. Macroseismic and instrumental magnitudes are taken from the Catalogo Parametrico dei Terremoti Italiani (CPTI15) Version 4 (Rovida et al. 2020, see Data and Resource section). Earthquakes in volcanic areas of Mt. Etna, Mt. Vesuvius, Ischia Island, and Campi Flegrei are excluded. The average difference between macroseismic and instrumental magnitudes in the last decade of the catalogue from 2010 to 2019 is -0.18 ± 0.09 while it was $+0.19 \pm 0.02$ in the previous 45-year period from 1965 to 2009.

One possible explanation given by Vannucci et al. (2021) was the progressive adoption by the Italian macroseismic investigators of the European Macroseismic Scale (EMS, Grünthal 1998) in place of the Mercalli Cancani Sieberg (MCS, Sieberg 1912, 1932) scale mostly used up to 2009, but such explanation remains purely hypothetical.

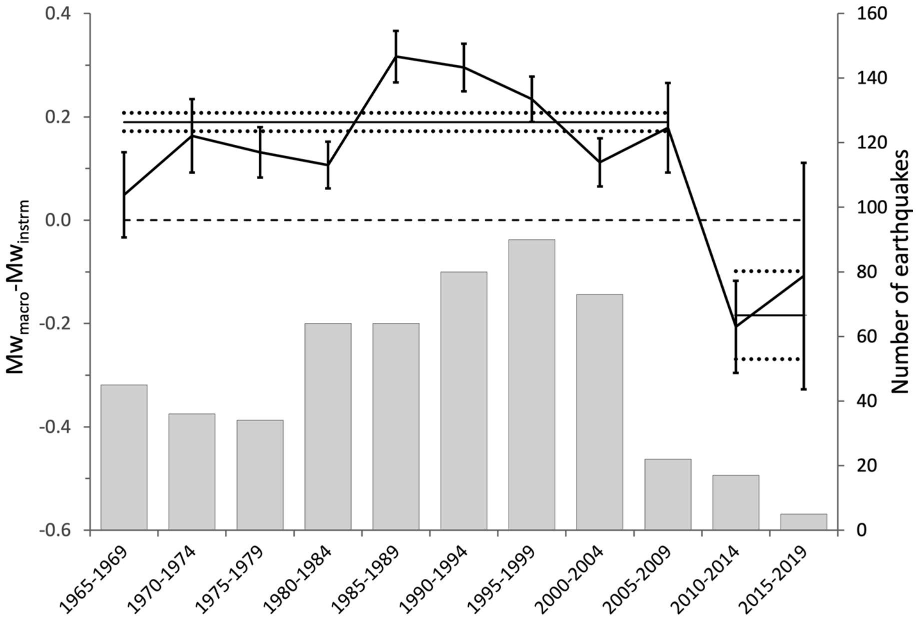

Fig. 1 Average differences between macroseismic (Mw_{macro}) and instrumental ($Mw_{instrum}$) magnitudes (solid thick line) and number of earthquakes used for the comparison (gray bars) over 5 year time intervals from the Catalogo Parametrico dei Terremoti Italiani (CPTI15) catalogue version 4 (See Data and resource section). Error bars indicate the standard errors (1 σ) of the mean differences. Thin solid lines indicate the average differences in the intervals 1965–2009 (0.19 ± 0.02) and 2010–2019 (-0.18 ± 0.09), dotted lines, the standard errors (1 σ) of average differences in such intervals. Earthquakes in volcanic areas of Mt. Etna, Mt. Vesuvius, Ischia Island, and Campi Flegrei are excluded

A recent paper by Del Mese et al. (2023) addresses the problem of comparing macroseismic intensity estimates made using the MCS scale and the EMS. This kind of analysis is very interesting because it was missed by the authors of the EMS scale even during the testing period between the first release of the scale in 1993 and the final one in 1998.

A comparison between different macroseismic scales, including EMS and MCS was presented by Musson et al. (2010). They conclude that there are no significant differences between EMS-98 and MCS except for degree 12 (see their Table 2). However, in their conclusion 3, they assert that "Experience seems to show that MCS intensity assignments are frequently higher than those in EMS for the same data despite the fact that assigning EMS intensities to the MCS scale descriptions themselves generally leads to equality in our opinion. The difference may lie in the way in which the scale has been interpreted; this point needs to be investigated further.". Unfortunately, they have never made such further investigation, to our knowledge at least. Based on theoretical arguments, Del Mese et al. (2023) infer that MCS intensity estimates in a contemporary settlement, where many buildings are made of reinforced concrete (RC), which was instead almost completely absent at the time the scale was compiled by Sieberg (1912, 1932), tend to be lower if compared to those made by EMS because the latter appropriately considers the lower vulnerability of RC buildings. The positive difference between EMS and MCS might reach up to one intensity degree in settlements, such as those recently rebuilt after a destructive earthquake, where most buildings belong to EMS vulnerability class C or higher.

Even if such a theoretical argument appears absolutely sound, it is contradicted by the empirical evidence shown by Vannucci et al. (2021) (see their Table 2) that the average difference between ("all") intensities estimated by the EMS and the MCS scales in Italy is slightly but significantly negative (-0.057 ± 0.025 degrees). The difference is more negative (-0.591 ± 0.046 degrees) for the MCS intensities estimated by Graziani et al. (2015) for "old town centers" struck by the 2012 Emilia sequence by selecting only the building types (in masonry) that were similar to those existing at the time when Sieberg (1912, 1932) defined the MCS scale (see Ferrari and Guidoboni 2000 and Vannucci et al. 2015 for English translations of the MCS scale from the German original of Sieberg).

The difference is clearly positive (about 0.2–0.3 degrees) only for the intensities estimated by Galli et al. (2012a, b) according to the version of the MCS scale proposed by Molin (2003, 2009) for the purpose of emergency macroseismic survey for civil protection uses. The latter consists of a complete re-modulation of the MCS scale with the addition of a new intensity degree (V-VI) and the addition and/or the modification of many percentages of damaged buildings (10 over 18) for the various degrees with respect to the original MCS scale (see Galli et al. 2012a and the Supplemental material of Vannucci et al. 2021 for English translations of most relevant tables of Molin 2009).

The differences between MCS and EMS are unexpected because one of the main intentions of EMS authors for the creation of the new scale was not to change the internal consistency of the scale. In particular, in the introduction of the EMS-98 booklet (Grünthal 1998) the reclassification of all earlier intensity assessments using the new scale is explicitly discouraged.

However, as already noted by Vannucci et al. (2021) and Molin (2009), the EMS does not derive directly from the MCS but rather from the Medvedev-Sponeur-Karnik (MSK) scale (Medvedev et al. 1967; Medvedev 1977). It is therefore possible that, as a result of various redefinitions over the decades, MSK had lost its strict connection with MCS or with the way the MCS was applied in Italy by some researchers (e.g., Ferrari and Guidoboni 2000, hereinafter F&G) so that the EMS, which is based on the MSK, might no longer be compatible with the MCS.

Even the average difference between the MCS and the Molin scales is unexpected because the intention of the author of the latter was only to rationalize and speed up the application of the scale, but preserving the consistency with the Sieberg (1932) definitions.

In the following, we present a degree-by-degree comparison between the EMS scale by Grünthal (1998), the original MCS scale by Sieberg (1932), and the Molin (2009) scale in order to understand if they are equivalent or not.

2 Comparison of grades of macroseismic scales

As the Molin scale does not consider at all the type and the vulnerability of the buildings and the MCS mentions only sporadically the quality of the buildings (badly or solidly built), we eliminate most references to the vulnerability of the buildings from the EMS. To do that, we assume the EMS vulnerability class B as representative of the generality of buildings considered by the MCS and Molin scales, class A of badly built, and class C of solidly built buildings mentioned by the MCS for degrees VI and VII. Damage to buildings with Earthquake Resistant Design (ERD) is ignored (EMS vulnerability classes D to F) because it cannot be compared with MCS and Molin diagnostics. Moreover, such vulnerability classes reasonably concern only the buildings rebuilt in the areas hit by recent strong earthquakes (e.g. L'Aquila, 2009 and Pianura Emiliana, 2012), hence they still represent only a very small portion of the total. We also ignore the mentions of MCS to wooden frame houses ("Fachwerkbau" in German) that were common in northern Europe at the beginning of the XX century, but which were and are now almost totally absent in Italy.

Our assumption of a default vulnerability class B is somehow at odds with Del Mese et al. (2023) which assessed instead a vulnerability class A for most buildings. However, they analyzed some relatively small settlements located in hilly or mountainous areas in the countryside where sourcing good quality building materials can be more difficult and the state of conservation and maintenance can be worse than in larger towns.

For the scope of this comparison, we also ignore all the descriptions of the effects on the environment (landslides, rock falls, emissions of water, sand, and mud from sea, lakes, and rivers) as well as the damage to man-made works other than buildings (dikes, dams, pipelines, rails, etc.), mentioned by the MCS but ignored by the EMS and Molin scales.

Regarding quantities, we assume that 5% of the Molin scale corresponds to "few" of MCS and of EMS (0–10%), the term "many" and the fraction 1/4 of MCS, and the percentage 25% of Molin to "many" of EMS (20–50). Actually, Molin (2003, 2009) associates the terms "many" and "numerous" of the MCS with the fraction 1/2 (50%), for which he also indicates the range of 40–60% (not reported by Sieberg 1932). We believe that our choice is more reasonable because 25% is closer to the midpoint (35%) of the EMS class "many" than 50%, which instead corresponds to the upper limit of the interval. Furthermore, in our analysis, we indicate the fraction 1/2 of MCS and the percentage 50% of Molin with "very many" whereas there is no correspondence with the EMS. Finally, we assume the correspondence of the fraction 3/4 of MCS and of the percentage 75% of Molin to "most" of EMS (60–100%), as well as the correspondence of 100% of Molin to "all" of MCS and EMS.

Regarding the levels of damage, we assume a one-to-one correspondence of the five grades of EMS with the five levels indicated by Molin, while for MCS we assume that "light damage" corresponds to grade 1, "moderate damage" to grade 2, "become uninhabitable" to grade 3, "destruction" to grade 4 and "collapse" to grade 5.

In the following, we will estimate a positive or negative difference of one degree of intensity between two compared scales when the diagnostics for a given degree of the first scale correspond to those of the previous or subsequent degree of the other scale. We estimated one-half of a degree of difference when this occurs only for about one-half of the diagnostics. If only one or two diagnostics concerning persons and objects are different, we consider the two scales as substantially equivalent for such a degree.

2.1 Effects on persons and on objects different from buildings

We show first in Table 1a, 1b, 1c the comparison between the three scales, limited to the effects on the persons and on the objects different from buildings. In the first column, we report the intensity degree with Roman numerals, in the second one, the integral text of the MCS scale (translated to English by Vannucci et al. 2015), where the effects on the environment are evidenced with italic typing and the effects on persons and objects different from buildings in boldface. In the third column, we report our simplified version of the latter descriptions, in the fourth column the integral text of EMS points (a) and (b), in the fifth column, our simplified version of them, and in the last column, the English translation of the effects on persons from Table 2 of Molin (2009).

For degrees I and II there are no significant differences among the three scales. For degree III we can note that EMS introduces the light swing of hanging objects which is absent in the other two scales. This is an innovation boasted by EMS which, however, does not influence much the evaluation of the degree as the lack of the indication of such an effect in modern buildings might simply be due to the lack of hanging objects. Hence, even for this degree, the differences among the three scales are almost negligible.

For degree IV, the most significant differences between MCS and EMS consist of the indication of little fear for MCS and no fear for EMS, the mention of moving liquids in MCS but not in EMS, and the swing of hanging objects in EMS but not in MCS. Molin ignores all effects other than the feelings of persons, which can be considered equivalent to the other scales. In summary, even for degree IV, there are not particularly significant differences between the three scales.

For degree V, the feeling by persons is slightly weaker for MCS (“many outdoors”) and EMS (“most indoors, few outdoors”) than for Molin (“almost all”). Hence, based on the effect on persons, it is possible that the Molin scale estimates a lower intensity than the other two. The other two scales also mention the people (frightened) running outdoors, the awakening of many sleepers, and some other effects on objects that are substantially equivalent to each other, except for the swing of hanging objects for which the EMS adds the adverb “considerably”, the mention of sound of doorbells and of flickering of electric lights (which are effects, somewhat obsolete in modern settlements) by MCS and of the uneasiness of animals by EMS. Hence, the effects on persons and objects are slightly stronger for EMS than for MCS. In summary, EMS and Molin provide lower intensities (of about one-half of a degree) with respect to MCS, even considering that EMS and Molin also include light damage to buildings for this degree (see below) whereas the MCS does not.

Since degree VI, we have no more effects on persons and objects reported by the Molin scale. The feeling by persons is slightly stronger for MCS (“by all”) than for EMS (“by most indoors and many outdoors”), whereas the effects on objects are somehow equivalent. The main differences are the mention by the MCS of the (strong) motion of liquids and of the ringing of belltowers’ clocks, and by the EMS the frightening of farm animals.

Table 1 Effects on persons and objects different from buildings

Degree	MCS	MCS in short	EMS98	EMS98 in short	Molin 2003
I	**noticed only by seismographs**	Not felt	a) Not felt, even under the most favourable circumstances. b) No effect.	Not felt	Not felt
II	**felt only by a few isolated subjects who are perfectly quiet, nervous or very sensitive, and almost exclusively in the upper floors of buildings**	Felt by very few indoors	a) The tremor is felt only at isolated instances (<1%) of individuals at rest and in a specially receptive position indoors. b) No effect.	Felt by very few indoors	Felt by very few in quiet
III	**even in densely populated areas the quake is felt as a shock by only a small part of the inhabitants who are inside their houses, as a vibration and like the fast passing of a car. By some it is recognized as an earthquake only after a reciprocal exchange of ideas**	Felt by few indoors	a) The earthquake is felt indoors by a few. People at rest feel a swaying or light trembling. b) Hanging objects swing slightly.	Felt by few indoors Hanging objects swing slightly	Felt by few in quiet
IV	**not many of the people who are outside of the buildings feel the earthquake. Inside the houses it is certainly identified by many but not all persons, in consequence of the trembling or slight swaying movement of the furniture and of the glassware and china which, put close to each other, knock against each other, like at the passing of a heavy truck on bumpy pavement. Windows tinkle, doors, beams and floorboards creak, the ceilings crackle. In open vessels, liquids can be slightly moved. One has the impression that, inside of the house, a heavy object (sack, furniture) is being overturned or that one is swaying together with the entire chair or bed etc., like a ship on a rough sea. This movement causes little fear, except in case of persons who became nervous or fearful because of previous earthquakes. Sleepers in very few cases wake up.**	Felt by many indoors, by few outdoors Few sleepers awake Little fear Furniture trembling or slightly swaying Glassware and china knocking Windows tinkle Doors, beams and floorboard creak Ceiling crackle Liquids slightly moved	a) The earthquake is felt indoors by many and felt outdoors only by very few. A few people are awakened. The level of vibration is not frightening. The vibration is moderate. Observers feel a slight trembling or swaying of the building, room or bed, chair etc. b) China, glasses, windows and doors rattle. Hanging objects swing. Light furniture shakes visibly in a few cases. Woodwork creaks in a few cases.	Felt by many indoors, by very few outdoors A few people awake No fear A few light furniture shake China, glasses, windows and doors rattle A few woodwork creak Hanging objects swing	Felt by many in quiet by few in motion
V	**even during full daily activity the earthquake is felt by many people in the streets or otherwise located outdoors. In apartments the earthquake is noticed because of the shaking of the entire building. Plants and twigs as well as the branches of bushes or thin trees move visibly as by a moderate**	Felt by many outdoors Few people run outdoors Sleepers generally awake	a) The earthquake is felt indoors by most, outdoors by few. A few people are frightened and run outdoors. Many sleeping people awake. Observers feel a strong shaking or rocking of the whole building, room or furniture.	Felt by most indoors, by few outdoors A few people were frightened and ran outdoors Many sleeping people awake	Felt by almost all in quiet and in motion, even sleeping

Table 1 (continued)

	wind. Free hanging objects swing, like for example curtains, suspended traffic lights, hanging lamps, and not too heavy chandeliers; doorbells start to sound, pendulum-clocks stop or oscillate with a wider movement, depending on whether the direction of the shock is perpendicular or parallel to the direction of the oscillation of the pendulum; thus, stopped pendulum-clocks may start functioning again; clock-springs resound; electric lights flicker or are interrupted owing to the contact of cable wires; pictures beat clattering against walls, or shift; spilled liquids in small amounts from well-filled open vessels; knickknacks and small objects as well as objects leaning against the walls may fall over; light furniture may even slightly move from their place; the furniture rattles; doors and shutters swing open or shut; windows panes break. General awaking of sleeping persons. In some isolated cases the inhabitants run outdoors	Light furniture may move Furniture rattles Small objects fall Pictures clatter against walls Doors and shutters swing open and shut Liquids small spills from well filled Free hanging objects swing Doorbells start to sound Electric light flicker	b) Hanging objects swing considerably. China and glasses clatter together. Small, top-heavy and/or precariously supported objects may be shifted or fall down. Doors and windows swing open or shut. In a few cases window panes break. Liquids oscillate and may spill from well-filled containers. Animals indoors may become uneasy.	China and glasses clatter A few small objects shift or fall Doors and windows swing open or shut. Liquids oscillate and may spill Hanging objects swing considerably Animals indoors uneasy	
V-VI					
VI	**the earthquake is felt by all with fear: therefore many run outdoors, some believe they will fall. Liquids move quite strongly; pictures, books, and similar objects fall from walls and shelves; break of dishes; rather stable household appliances and even few pieces of furniture are moved or fall; smaller bells in chapels and churches, clocks of bell-towers ring. In single, solidly built houses there is slight damage; cracks in the plaster, falling of plaster from walls and ceilings. Stronger, but still harmless damage on badly constructed buildings. Few roof tiles or chimney bricks may fall**	Felt by all with fear Many people run outdoors Some people believe to fall Household appliances and few pieces of furniture move or fall Pictures fall from walls Books fall from shelves Dishes breaks Liquids move strongly Clocks of belltowers ring	a) Felt by most indoors and by many outdoors. A few persons lose their balance. Many people are frightened and run outdoors. b) Small objects of ordinary stability may fall and furniture may be shifted. In few instances dishes and glassware may break. Farm animals (even outdoors) may be frightened.	Felt by most indoors and by many outdoors. Many people frightened and run outdoors A few people lose balance Furniture may be shifted Small object may fall A few dishes and glassware break Farm animals may be frightened even outdoors	
VII	**remarkable damage is caused to the apartment furnishings, even to the very heavy ones, which in large number are**		a) Most people are frightened and try to run outdoors. Many find it	Many people find difficult to stand, especially on upper floors	

Table 1 (continued)

	overturned or smashed. Larger church bells ring. *Watercourses, ponds and lakes begin to wave and become turbid because of the moving slime. Sporadic slidings of sandy and pebbly banks. Water level in the wells changes* Moderate damage to numerous solidly built buildings: small cracks in walls, fall of rather big parts of the plastering and stucco work, and bricks; general sliding of roof tiles. Many chimney-pots are damaged by cracks, by falling of roof tiles and stones; ruined chimney-pots fall on the roof damaging it. Badly fixed decorations fall from towers and high buildings. In wooden frame houses the damage to the plastering and panel walls is even worse. In isolated cases collapse of poorly built or preserved houses	Even very heavy furniture overturned or smashed Larger church bell ring	difficult to stand, especially on upper floors. b) Furniture is shifted and top-heavy furniture may be overturned. Objects fall from shelves in large numbers. Water splashes from containers, tanks and pools.	Most people frightened and try to run outdoors Furniture shifted and some overturned Many objects fall from shelves Water splashes from containers, tanks and pools	
VIII	*entire tree trunks sway lively or even break off.* **Even the heaviest furniture is sometimes moved far from its position or overturned. Statues, pillars and similar located on the ground or even in churches, cemeteries and public parks etc. turn on their pedestal or fall. Solid stone fences are torn apart and knocked down** About 1/4 of the houses reports heavy destructions; some collapse, many become uninhabitable. In wooden frame houses, the panel walls fall out mostly. Wooden houses are squashed or overturned. In particular, the falling of church towers and factory chimneys may cause to nearby buildings heavier damage than the action of the earthquake only. *Fissures are formed in steep slopes and wet grounds; sand and mud come out of wet grounds*	Some heaviest furniture moved far Statues and pillars turn or fall	a) Many people find it difficult to stand, even outdoors. b) Furniture may be overturned. Objects like TV sets, typewriters etc. fall to the ground. Tombstones may occasionally be displaced, twisted or overturned. Waves may be seen on very soft ground.	Many people find it difficult to stand, even outdoors. Furniture may be overturned. Some medium size objects displaced, twisted or overturned A few tombstones displaced, twisted or overturned. Waves may be seen on very soft ground.	
IX	about 1/2 of the stone houses is heavily destroyed; a certain number of them collapses; the largest part becomes uninhabitable. Wooden frame houses are pulled up from their own foundations and squashed, this way sometimes the support beams are cut, thus considerably contributing to destroy the houses		a) General panic. People may be forcibly thrown to the ground. b) Many monuments and columns fall or are twisted. Waves are seen on soft ground.	People may be forcibly thrown to the ground. General panic. Many monuments and columns fall or are twisted. Waves are seen on soft ground.	

However, such effects should not influence much the assignment of this degree, which is based mostly on effects on buildings (see section “Effects on buildings” below).

For degree VII, there is a fair correspondence between the MCS and EMS only on the possible overturning of pieces of furniture, but the MCS also mentions the ringing of large church bells (somewhat obsolete) and the EMS, most people frightened running outdoors, many people finding difficult to stand and the water splashing from containers, tanks, and pools. Even if for this degree the assignment is mostly based on effects on buildings, other effects are compatible with slightly lower EMS intensities (as it indicates more effects) with respect to MCS.

For degree VIII, only EMS still reports effects on persons (“many find it difficult to stand even outdoors”). The effects on furniture are comparable between MCS and EMS,

Table 2 Effects on buildings

Degree	MCS	MCS in short	EMS98	EMS98 in short	Molin 2003	Ferrari& Guidoboni 2000
V	even during full daily activity the earthquake is felt by many people in the streets or otherwise located outdoors. In apartments the earthquake is noticed because of the shaking of the entire building. Plants and twigs as well as the branches of bushes or thin trees move visibly as by a moderate wind. Free hanging objects swing, like for example curtains, suspended traffic lights, hanging lamps, and not too heavy chandeliers; doorbells start to sound, pendulum-clocks stop or oscillate with a wider movement, depending on whether the direction of the shock is perpendicular or parallel to the direction of the oscillation of the pendulum; thus, stopped pendulum-clocks may start functioning again; clock-springs resound; electric lights flicker or are interrupted owing to the contact of cable wires; pictures beat clattering against walls, or shift; spilled liquids in small amounts from well-	No damage	**c) Damage of grade 1 to a few buildings of vulnerability class A and B.**	Level 1 to few buildings	Level 1 in few (5%) buildings	No damage
	filled open vessels; knickknacks and small objects as well as objects leaning against the walls may fall over; light furniture may even slightly move from their place; the furniture rattles; doors and shutters swing open or shut; windows panes break. General awaking of sleeping persons. In some isolated cases the inhabitants run outdoors					
V-VI					Level 1 in many buildings (25%) *Level 2 in few (5%) buildings*	
VI	the earthquake is felt by all with fear: therefore many run outdoors, some believe they will fall. Liquids move quite strongly; pictures, books, and similar objects fall from walls and shelves; break of dishes; rather stable household appliances and even few pieces of furniture are moved or fall; smaller bells in chapels and churches, clocks of bell-towers ring. **In single, solidly built houses there is slight damage; cracks in the plaster, falling of plaster from walls and ceilings.**	Light damage in a few solid buildings *Moderate damage on badly constructed buildings*	**c) Damage of grade 1 is sustained by many buildings of vulnerability class A and B; a few of class A and B suffer damage of grade 2; a few of class C suffer damage of grade 1**.	Grade 1 to few solid buildings (C) Grade 1 to many buildings *Grade 2 to few buildings*	Level 1 in very many (50%) buildings *Level 2 in many (25%) buildings* **Level 3 in few (5%) buildings**	Damage

Table 2 (continued)

	Stronger, but still harmless damage on badly constructed buildings. Few roof tiles or chimney bricks may fall					
VII	remarkable damage is caused to the apartment furnishings, even to the very heavy ones, which in large number are overturned or smashed. Larger church bells ring. *Watercourses, ponds and lakes begin to wave and become turbid because of the moving slime. Sporadic slidings of sandy and pebbly banks. Water level in the wells changes* **Moderate damage to numerous solidly built buildings: small cracks in walls, fall of rather big parts of the plastering and stucco work, and bricks; general sliding of roof tiles. Many chimney-pots are damaged by cracks, by falling of roof tiles and stones; ruined chimney-pots fall on the roof damaging it. Badly fixed decorations fall from towers and high buildings. In wooden frame houses the damage to the plastering**	*Moderate damage in numerous solidly built buildings* ***Collapse in isolated poorly built***	**c) Many buildings of vulnerability class A suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class B suffer damage of grade 2; a few of grade 3. A few buildings of vulnerability class C sustain damage of grade 2.** *A few buildings of vulnerability class D sustain damage of grade 1.*	*Grade 2 to some solidly built (C) buildings* *Grade 2 to many buildings* **Grade 3 to few buildings. Grade 3 to many poorly built (A) buildings.** ***Grade 4 in a few poorly built (A) buildings***	*Level 2 in very many (50%) buildings* **Level 3 in many (25%) buildings** ***Level 4 in few (5%) buildings***	Damage without widespread collapse
	and panel walls is even worse. In isolated cases collapse of poorly built or preserved houses					
VIII	*entire tree trunks sway lively or even break off.* Even the heaviest furniture is sometimes moved far from its position or overturned. Statues, pillars and similar located on the ground or even in churches, cemeteries and public parks etc. turn on their pedestal or fall. Solid stone fences are torn apart and knocked down **About 1/4 of the houses reports heavy destructions; some collapse, many become uninhabitable. In wooden frame houses, the panel walls fall out mostly. Wooden houses are squashed or overturned. In particular, the falling of church towers and factory chimneys may cause to nearby buildings heavier damage than the action of the earthquake only.** *Fissures are formed in steep slopes and wet grounds; sand and mud come out of wet grounds*	**Strong damage of many buildings (uninhabitable)** ***Destruction of many buildings*** ***Collapse of some buildings***	**c) Many buildings of vulnerability class A suffer damage of grade 4; a few of grade 5. Many buildings of vulnerability class B suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class C suffer damage of grade 2; a few of grade 3.** *A few buildings of vulnerability class D sustain damage of grade 2.*	**Grade 3 to many buildings** ***Grade 4 to a few buildings***	**Level 3 in very many (50%) buildings** ***Level 4 in many (25%) buildings*** ***Level 5 in few (5%) buildings***	The set of buildings as a whole have been widely and seriously affected but collapse is of minor statistical importance

Table 2 (continued)

IX	**about 1/2 of the stone houses is heavily destroyed; a certain number of them collapses; the largest part becomes uninhabitable. Wooden frame houses are pulled up from their own foundations and squashed, this way sometimes the support beams are cut, thus considerably contributing to destroy the houses**	**Strong damage of most buildings (uninhabitable)** ***Destruction of very many buildings*** ***Collapse of some (or many) buildings***	**c) Many buildings of vulnerability class A sustain damage of grade 5.** **Many buildings of vulnerability class B suffer damage of grade 4; a few of grade 5. Many buildings of vulnerability class C suffer damage of grade 3; a few of grade 4.** *Many buildings of vulnerability class D suffer damage of grade 2; a few of grade 3. A few buildings of vulnerability class E sustain damage of grade 2.*	***Grade 4 to many buildings*** ***Grade 5 to a few buildings***	**Level 3 in most (75%) buildings** ***Level 4 in very many (50%) buildings*** ***Level 5 in many (25%) buildings***	The majority of buildings are unfit for habitation
X	**heavy destruction of about 3/4 of the buildings; most of them collapse** *Even well-built wooden buildings and bridges suffer severe damage, some are also destroyed. Dikes and dams, etc. are more or less significantly damaged, rails are slightly bent and pipes*	***Destruction of most buildings*** ***Collapse of very many buildings***	**c) Most buildings of vulnerability class A sustain damage of grade 5.** **Many buildings of vulnerability class B sustain damage of grade 5.**	***Grade 5 to many buildings***	***Level 4 in most (75%) buildings*** ***Level 5 in very many (50%) buildings***	Destruction of three quarters of buildings with a large percentage in a state of total collapse
	(gas-water and sewer mains) are sheared, broken or crushed. Fissures and, due to the pressure, broad undulating folds are formed in the paved and asphalted layer of the roads *In the soft, and especially wet ground, fissures, even up to several tens of centimeters width, are formed; in particular parallel to the water courses, up to one meter cracks are formed. Not only does soft ground slide from the slopes under the form of a landslide, but also entire boulders role towards the valley under the form of falling rocks. Big rocks break off the river banks and the steep coasts. On the low coasts sand and mud masses are moved; thus the relief of the ground sometimes undergoes not secondary changes. Water level in the wells changes frequently. From rivers, canals and lakes etc. the water is thrown onto the shores*		**Many buildings of vulnerability class C suffer damage of grade 4; a few of grade 5.** *Many buildings of vulnerability class D suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class E suffer damage of grade 2; a few of grade 3. A few buildings of vulnerability class F sustain damage of grade 2.*			
XI	**Collapse of all stone buildings. Solid wooden buildings and resilient**	***Collapse of all buildings***	**c) Most buildings of vulnerability class B sustain**	***Grade 5 to most buildings***	***Level 5 in most (75%) buildings***	Almost total destruction of buildings

Table 2 (continued)

	wooden joint huts only sporadically withstand. *Even the bigger and safer bridges collapse due to the breaking of the stone pillars or to the bending of the iron pillars. Dikes and dams are often completely torn apart on long stretches; rails are strongly bent and compressed. Pipelines in the ground are completely torn apart and become unusable The ground undergoes various, considerable changes, which are determined by the nature of the soil: wide cracks and fissures open up, especially in soft and wet grounds there is a considerable horizontal and vertical disruption. For this still, there is leakage of sand and mud leading water in its different manifestations. The cleavages of the ground and the rocks falls are numerous*		**damage of grade 5. Most buildings of vulnerability class C suffer damage of grade 4; many of grade 5.** *Many buildings of vulnerability class D suffer damage of grade 4; a few of grade 5. Many buildings of vulnerability class E suffer damage of grade 3; a few of grade 4. Many buildings of vulnerability class F suffer damage of grade 2; a few of grade 3.*			(abandoned sites reconstructed elsewhere)
XII	**no man-made work withstands.** *The transformation of the ground takes the greatest dimensions. Accordingly, water flows, under and above the ground,*	No man-made work withstands	**c) All buildings of vulnerability class A, B and practically all of vulnerability class C are destroyed.**	***Grade 5 to all buildings***	***Level 5 in all (100%) buildings***	Not attributed
	undergo the most various changes: waterfalls and lakes formed, rivers diverted etc		*Most buildings of vulnerability class D, E and F are destroyed. The earthquake effects have reached the maximum conceivable effects.*			

Table 3 Graphic comparison between macroseismic scales

<table>
<tr><th>EMS</th><th>MCS no RC</th><th>Molin no RC</th><th>MCS RC</th><th>Molin RC</th></tr>
<tr><td>I</td><td>I</td><td>I</td><td>I</td><td>I</td></tr>
<tr><td>II</td><td>II</td><td>II</td><td>II</td><td>II</td></tr>
<tr><td>III</td><td>III</td><td>III</td><td>III</td><td>III</td></tr>
<tr><td rowspan="2">IV</td><td>IV</td><td rowspan="2">IV</td><td>IV</td><td rowspan="2">IV</td></tr>
<tr><td>V</td><td>V</td></tr>
<tr><td>V</td><td rowspan="2">VI</td><td>V</td><td rowspan="3">VI</td><td>V</td></tr>
<tr><td>VI</td><td>V-VI</td><td>V-VI</td></tr>
<tr><td>VII</td><td rowspan="2">VII</td><td>VI</td><td>VI</td></tr>
<tr><td rowspan="2">VIII</td><td>VII</td><td rowspan="2">VII</td><td rowspan="2">VII</td></tr>
<tr><td rowspan="2">VIII</td><td rowspan="2">VIII</td></tr>
<tr><td rowspan="2">IX</td><td rowspan="2">VIII</td><td rowspan="2">VIII</td></tr>
<tr><td rowspan="2">IX</td><td rowspan="2">IX</td></tr>
<tr><td rowspan="2">X</td><td rowspan="2">IX</td><td rowspan="2">IX</td></tr>
<tr><td rowspan="2">X</td><td>X</td></tr>
<tr><td rowspan="2">XI</td><td rowspan="2">XI</td><td rowspan="2">X</td><td>X</td></tr>
<tr><td rowspan="2">XI</td><td>XI</td></tr>
<tr><td>XII</td><td>XII</td><td>XI</td><td>XII</td></tr>
</table>

the MCS mentions the turning or falling of statues and pillars whereas the EMS the twisting and overturning of medium-sized objects and the possible observation of waves in very soft ground (whatever this means). These should not influence much the assessment of the degree that is mainly entrusted to effects on buildings.

For degree IX, the MCS does not report any effect on persons and objects whereas the EMS indicates general panic, people forcibly thrown to the ground, falling or twisting of monuments and columns (the latter very similar to an effect reported by the MCS for degree VIII) and the probable observation of waves on soft ground. Also, in this case, the effects on people and objects would favor (although not necessarily lead to) EMS intensities lower than MCS.

For degrees X to XII, no effects on persons or objects are indicated by any of the scales.

2.2 Effects on buildings

The comparison of the effects on buildings is shown in Table 2a, 2b, 2c, 2d. In the second column, we report the integral text of the MCS scale with effects on buildings evidenced in boldface, in the third one, our simplified version of the latter, in the fourth one, the integral text of EMS point c), in the fifth one, our simplified version of the latter, in the sixth one the expression in words of Table 5 of Molin (2009) (as reported in Table 2 of Galli et al. 2012a) and in the last column the key criteria for the application of MCS scale as indicated by F&G. A graphic summary of the comparison of the three scales is reported in Table 3.

For degrees from I to IV, no effects on buildings are reported by any scale.

For degree V, the MCS and F&G do not report effects on buildings, whereas the EMS and the Molin report light damage to a few buildings. The inclusion of the latter effects in this degree might bring lower intensities from one-half to one degree of the EMS and Molin with respect to the MCS. Considering that even the effects on persons and objects are stronger for EMS, we may argue that on average, the EMS intensities might be lower than MCS up to one degree (V instead of VI). As the Molin scale reports light damage to a few buildings, it could estimate lower intensities than the MCS up to one-half a degree.

Only the Molin scale includes a further degree named V–VI, reporting level 1 damage to many buildings and level 2 to a few buildings. Such effects well correspond to those reported by the EMS scale for degree VI. This might bring the Molin scale to be one-half of a degree lower than the EMS (and maybe even lower than MCS).

For degree VI, the MCS scale does not report effects for the generality of buildings but only for solidly (light damage to a few) and badly built ones ("stronger but still harmless", which can be assumed to correspond to moderate damage). Such effects do not differ much from some of those reported by the EMS (light damage to solid buildings, moderate damage to a few buildings) but are definitely lower than those reported by the Molin scale (level 1 damage to very many buildings, level 2 damage to many buildings, and level 3 damage to a few buildings). For F&G this degree is attributed only if there is some evidence of damage (but, implicitly, if there is also no evidence of severe damage). In summary, we can assert that the Molin scale provides intensities of about one degree lower than both the MCS and the EMS because the effects it reports almost correspond to those reported by the other scales for degree VII.

Even for degree VII, the MCS scale does not report effects for the generality of buildings but only for solidly (moderate damage in numerous) and badly built ones (collapse in very few). The first one exactly corresponds to EMS but the second one appears slightly stronger than that, implying lower MCS intensities than EMS. However, considering that for the effects on persons and objects, EMS underestimates the MCS (see above), we can infer that to this degree, MCS and EMS are substantially equivalent when considering all the effects. For F&G the degree VII can be attributed when there is damage to buildings, but the collapses are sporadic, which is in line with MCS and EMS. Concerning the Molin scale, we can note that the reported effects on buildings are generally stronger than that of the EMS (very many (50%) instead of many for level 2 damage, many instead of few for level 3 damage) and thus of the MCS. This might imply Molin intensities up to one degree lower than both MCS and EMS.

For degree VIII, the definitions of the Molin scale are very similar to those of MCS. The only difference is that Molin indicates very many (50%) buildings with level 3 damage whereas MCS indicates that many buildings become uninhabitable. However, we can consider the two scales almost equivalent for this degree. For F&G the set of buildings as a whole has been widely and seriously affected but collapse is of minor statistical importance, which is consistent with both MCS and Molin. Conversely, the effects reported by EMS are generally weaker than MCS and Molin: level 3 for many buildings (instead of very many), level 4 for a few buildings (instead of many), and the mention of level 5 damage only for a few badly built (class A) buildings. In summary, both MCS and Molin tend to provide intensities lower than EMS by about one-half of a degree at least.

Even for degree IX, the effects of MCS and Molin scales are about the same, whereas those of EMS are somehow weaker: level 4 damage for many buildings (instead of very many) and level 5 damage for a few buildings (instead of many). F&G indicate that this degree is assigned when the majority of buildings are unfit for habitation, which is equivalent to both MCS and Molin. Thus, MCS and Molin tend to estimate intensities about one-half a degree lower than EMS.

Analogously, for degree X the MCS and Molin are very similar, and the EMS indicates slightly weaker effects (level 5 damage for many buildings instead of very many). Hence, MCS and Molin tend to be lower with respect to EMS of about a one-half of a degree. For F&G the assignment of this degree is made when there is destruction of three quarters of buildings with a large percentage in a state of total collapse, well corresponding to both MCS and Molin.

For degree XI, both EMS and Molin, report level 5 damage for most buildings, whereas MCS for all buildings. Hence MCS would be lower with respect to EMS and Molin of about a one-half of a degree. F&G assign such a degree when there is almost total destruction of buildings, often associated with abandoned sites reconstructed elsewhere. A part for the word “almost”, this is the same picture indicated by MCS.

Finally, the MCS for degree XII indicates “no man-made work withstands” (whatever this means) whereas EMS and Molin, level 5 damage for all buildings, which is indicated by MCS for degree XI. Even in this case, MCS would be lower with respect to both EMS and Molin, although intensities XII had never been assigned in Italy.

3 Discussion and conclusions

The assessment of the macroseismic intensity is strictly dependent on the macroseismic scale and its indicators (type of effect, quantity of subjects affected by the effect, vulnerability). Each indicator is a variable influenced by additional factors and uncertainties that might impact on observations (e.g. cumulative effects, effects overlapping between

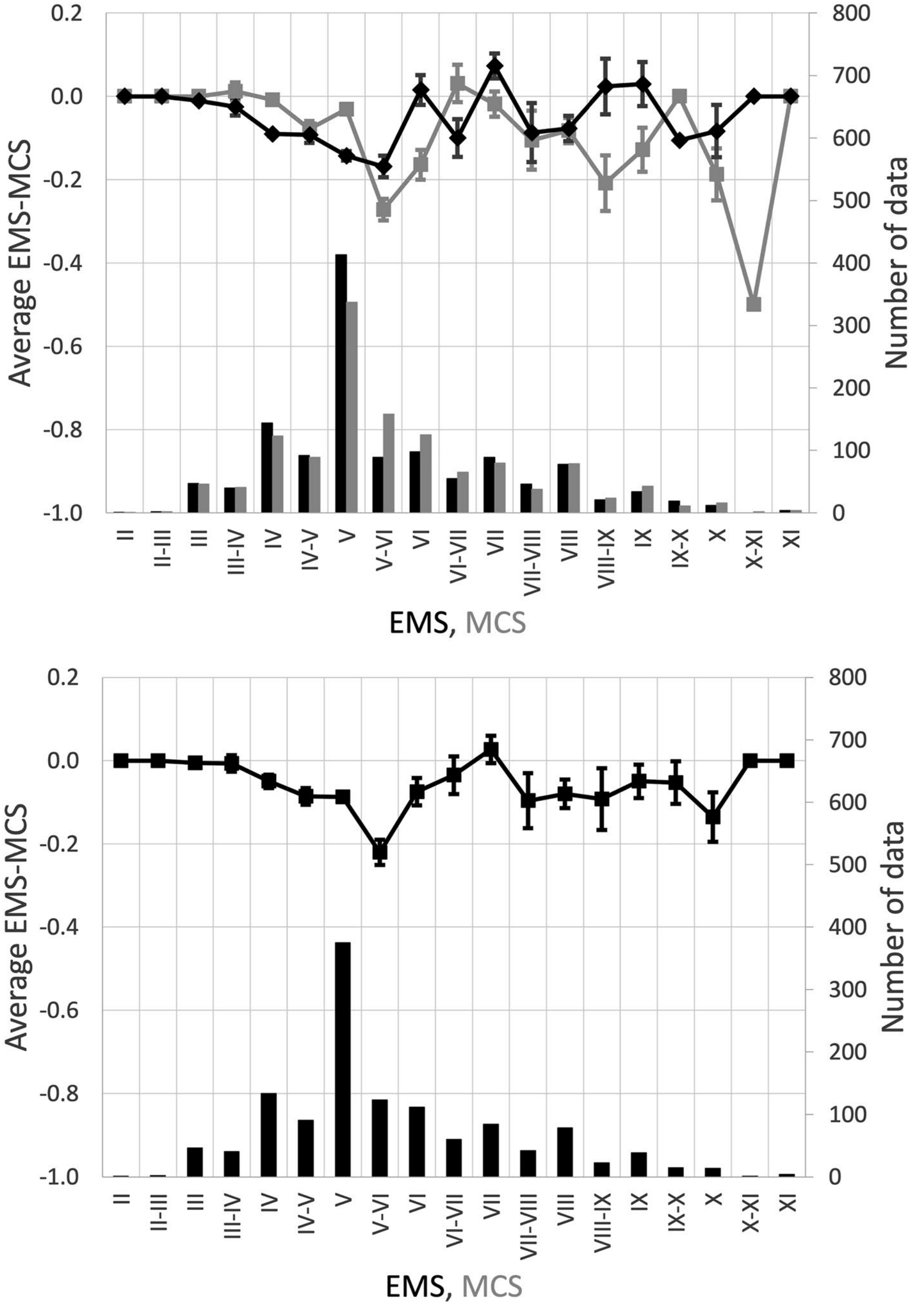

Fig. 2 Top: mean differences between EMS and MCS as a function of both EMS (black) and MCS (grey). Bottom: averages of the two

degrees, vulnerability of buildings), generating disparities between theoretical expectations and observed realities due to assumptions and subjective evaluations of the investigators.

Table 4 Average differences between EMS and MCS as a function of the degree

Intensity class	N	Δ	σ	t	p
III	47	− 0.005	0.008	0.707	0.483
III–IV	41	− 0.006	0.019	0.329	0.744
IV	134	− 0.049	0.016	3.081	**0.003**
IV–V	91	− 0.086	0.020	4.302	**0.000**
V	375	− 0.087	0.012	7.444	**0.000**
V–VI	124	− 0.220	0.031	7.174	**0.000**
VI	112	− 0.074	0.033	2.268	**0.025**
VI–VII	60	− 0.035	0.045	0.763	0.448
VII	85	0.027	0.033	0.827	0.410
VII–VIII	42	− 0.096	0.066	1.455	0.153
VIII	79	− 0.080	0.034	2.323	**0.023**
VIII–IX	23	− 0.092	0.074	1.246	0.226
IX	39	− 0.049	0.040	1.229	0.227
IX–X	15	− 0.053	0.051	1.029	0.320
X	14	− 0.135	0.059	2.279	**0.039**
X–XI	1	–	–	–	–
XI	4	0.000	0.000	–	–
All	1284	− 0.083	0.008	10.530	**0.000**

N: number of compared intensity estimates, Δ: average difference between EMS and MCS intensity estimates, σ: standard deviation of differences between EMS and MCS intensity estimates, t: Student's t statistics for the H_0 hypothesis $\Delta=0$, p: significance level of the H_0 hypothesis $\Delta=0$ (in boldface if $p<0.05$ and then the H_0 hypothesis can confidently rejected)

Hence, our formal comparison among macroseismic scales might be questioned as it contains a certain number of subjective judgments. However, we believe that it rather clearly shows that the definitions of the different degrees are not strictly equivalent to each other and in particular that the EMS, if applied literally, tends to provide slightly higher intensities than MCS and Molin scales, particularly at high degrees.

Such considerations hold for settlements where the fraction of buildings in RC or with some level of ERD is negligible (like for example the old town centers analyzed by Graziani et al. 2015). However, this is not the case in many modern towns and villages in Italy where the percentage of RC buildings is on average about 30% (as reported by Vannucci et al. 2021, based on data from the Istituto Nazionale di Statistica ISTAT). Such a percentage may be significantly higher in settlements rebuilt after destructive earthquakes. This means that the average vulnerability class may increase from B, which we have assumed for the generality of buildings, to C or even higher, if a significant amount of ERD is present. Based on the EMS scale, an average increase, of one vulnerability class would imply a decrease of one degree in the estimated intensity for degrees higher than VI. This means that the presence of about 30% of RC buildings, which mostly have vulnerability class C, does not change the EMS estimates, but reduces the estimates of both MCS and Molin by about one-half a degree. Even considering the overestimation of EMS with respect to MCS and Molin of about one-half of a degree inferred before for traditional settlements, we might reach an average overestimation of one degree for degrees higher than about VI (see in Table 3 the resulting graphic summary) which well corresponds with that inferred by Del Mese et al. (2023).

However, this overestimation does not seem to occur in the practice in Italy, since the estimates made by EMS are slightly but systematically lower on average than those made by the MCS (Table 2 in Vannucci et al. 2021, and references therein). To better understand this point, we report in Fig. 2 (top panel) the plot of the mean differences between EMS and MCS as a function of both EMS (black) and MCS (grey). The bars correspond to the 1-sigma errors of the mean values (corresponding to the standard deviation of the differences divided by the square root of the number of data). As the two curves as a function of EMS and MCS appear not very coherent from one to the other, we also plot in Fig. 2 (bottom panel) the average of the differences referred to both intensities. See also the numerical values of average differences and their errors in Table 4.

With respect to the datasets analyzed by Vannucci et al. (2021) and reported in their Table 2, we corrected a mistake regarding the number of data (86 and not 66) for the earthquake of 18/01/2017 (Rossi et al. 2019) and eliminated the data of the shock of 20/05/2012 and of the cumulate intensities of Emilia sequence of May 2012 because the MCS intensities were estimated using the Molin scale by Galli et al. (2012a, b). The total number of data considered is now 1284 and the overall EMS-MCS difference is -0.083 ± 0.008. In simple words, this means that, on average, the EMS is one-half a degree lower than MCS in one out of 6 localities. The differences at the various degrees are generally negative and, in most cases, significantly different from 0 (Table 4). They are close to 0 below degree IV and above degree X. The only positive average difference (but not significantly different from 0) is for intensity VII (0.027 ± 0.033). The minimum negative difference is for intensity V–VI (-0.220 ± 0.031).

Even if such negative differences are small, they, however, contradict the evidence of our degree-by-degree analysis and also of Del Mese et al. (2023) that would indicate a clear positive difference of one-half of a degree at least between EMS and MCS in modern settlements.

An aspect that might influence the intensity assignment for the EMS and explain why it might provide lower intensities with respect to MCS and not higher as it should be is the difficulty in evaluating the vulnerability of buildings. This is a very hard and time-consuming task, particularly for settlements larger than a countryside village (e.g. Tertulliani et al. 2011), and for such reason, it could be addressed through simplified approaches, with the consequence of introducing some kind of bias. Particularly in the absence of civil engineering specialists within the survey team, somebody might be tempted to base the vulnerability estimation on the level of damage suffered by the buildings. So, for example, collapsed or hardly destroyed buildings might be always assigned to class A whereas those with average damage levels to class B. In the absence of true engineering motivations for such assignments, the overall effect would be to incorrectly underestimate the estimated EMS intensity.

If we do not hypothesize an incorrect vulnerability assessment, the negative difference or even the substantial equivalence between EMS and MCS estimates in macroseismic surveys of modern settlements remains inexplicable.

3.1 Data and resource section

The Catalogo Parametrico dei Terremoti Italiani (CPTI15) (Rovida et al. 2020) Versione 4 data are collected at https://emidius.mi.ingv.it/CPTI15-DBMI15/download_CPTI15.htm (last accessed September 2023).

The intensity data used for the comparison between EMS and MCS of Fig. 2 were collected by Vannucci et al. (2021) from various websites listed in their Data and Resource section (all of them, last accessed in July 2020).

Acknowledgements We thank three anonymous referees for constructive criticisms and thoughtful suggestions that helped much to improve the paper. This work was partially supported by the European Union within the ambit of the H2020 Project RISE (Number 821115).

Author contributions All authors contributed to the study conception, design, material preparation, and analysis. All authors read and approved the final manuscript.

Funding Open access funding provided by Istituto Nazionale di Geofisica e Vulcanologia within the CRUI-CARE Agreement. This article benefitted from funding provided by the European Union within the ambit of the H2020 Project RISE (Number 821115).

Data availability There are no data produced by this work.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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