Murphy's Law and Learning from Natural Disasters

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Abstract

Learning from natural disasters is predominantly regarded as beneficial: Individuals and governments learn to cope and thereby reduce damage and loss of life in future disasters. We argue against this standard narrative and point to two principal dangers of learning from past disasters: First, investment in protective infrastructures may not only stimulate settlement in hazard-prone areas, it may also foster a false impression of security, which can prevent individuals from fleeing to safe places when hazard strikes. Second, if disaster events in the past did not have catastrophic consequences, affected individuals do not take future events sufficiently seriously. As a consequence, learning from disasters is a double-edged sword that can prevent large scale damage and human loss most of the time but results in the worst case scenario when a disaster occurs at an unexpected scale and public preparedness measures fail. We demonstrate the devastating impact of misplaced trust in public preparedness measures and misleading individual learning from past experience for the case of the 2011 Tohoku tsunami. Our descriptive and statistical analyses show that so many people died in this event because Japan is the most tsunami prepared country in the world, not despite of it.

> Man has three ways of learning. First, on meditation; that is the noblest. Secondly, on imitation; that is the easiest. Thirdly, on experience; that is the bitterest.
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> Attributed to Confucius, cited in Lee and Jones (2004, p. vii)

1. Introduction

Social scientists argue that natural disasters offer a window of opportunity for individuals and policy makers to learn and better adapt to natural hazards (Birkmann et al. 2010). For example, Lee and Jones' (2004) treatise on landslide risk assessment and Malone and Ho's (1995) analysis of learning from landslip disasters in Hong Kong both summarize the advantages of learning from previous disaster events. The dominant view is that at worst the lessons of disasters are ignored while at best learning from disasters leads to better adaptation or even prevention (Jasanoff 1994; Jongman et al. 2015).

We challenge this optimistic view. Learning from natural disasters has consequences that do not need to be beneficial. Rather, learning from disasters is a double-edged sword (Neumayer et al. 2014):[1] On the one hand, such learning increases public investment in infrastructures that protect and thus mitigate against the forces of nature and leads to a more appropriate reaction of affected people on an individual level. On the other hand, however, public and private investment into such infrastructures and the installation of early warning systems also stimulate a false notion of safety and

1 In Keefer et al. (2011), we argued that earthquake propensity reduces earthquake mortality, thus adopting the predominant view of learning from past natural disasters as being unambiguously positive. In Neumayer et al. (2014) we qualified this argument and accepted that the worst case scenario is one in which preventive measures failed. In this article, we develop further the logic that renders learning from natural disasters a double-edged sword.

encourage additional settlement in high-risk areas such as floodplains, the fault lines of tectonic plates, and low elevation areas near the coastline (Collenteur et al. 2015).[2]

Public safety measures also lure individuals into careless behaviour when hazard strikes. In the worst case, affected individuals delay leaving the endangered area or even stay in high-risk areas to watch the build-up of the disaster. Individual experience with hazard events that did not turn into large scale disasters has a very similar effect. Individuals who experienced numerous potential natural disasters – hazard events that did not cause much death or damage – will adjust and thus lower their risk perception for future disasters: If the last disasters proved harmless, why should the next one be dangerous?

Accordingly, when a very strong hazard strikes and safety devices fail, the human and economic losses of disasters become exacerbated (Hallegatte 2012; Neumayer et al. 2014: 8). Thus, one of the most important determinants of excessive disaster mortality and economic loss is failing disaster protection devices. In this article we use the example of the 2011 Tohoku earthquake and tsunami to demonstrate this ambiguous logic of learning from past disasters. We offer an answer to the puzzle how and why more than 18,000 people died or went missing in a country that had seemingly learned more from past disasters than any other country. No doubt, Japan's preparedness to earthquakes and tsunamis was unrivalled in the world at the time it was hit by the event.

We develop our argument in two steps. We start with providing evidence demonstrating that governments and individuals did indeed learn from historical

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[2] A similar problem arises if governments compensate disaster victims for their economic losses (Raschky and Weck-Hannemann 2007).

tsunami experiences, and we discuss the consequences of this learning process during the Tohoku tsunami. Misplaced trust in public disaster preparedness measures provided a false impression of safety and lured many into their death.

In a second step, we provide evidence that misleading experience with relatively harmless tsunamis in the recent past also stimulated imprudent behaviour. Employing a statistical analysis of mortality across the 88 municipalities that experienced a run-up of water of at least one metre high, we show that municipalities in which individuals had experienced tsunamis without fatalities during living memory had systematically higher mortality rates during the Tohoku tsunami than municipalities which had experienced actual tsunami mortality. In other words, the lesson that tsunamis are seemingly harmless in one's own municipality significantly increased the number of deaths during the Tohoku tsunami. Misleading experience influenced the expectations of many – expectations that turned out to be utterly inconsistent with the extreme hazard event of the 2011 tsunami for which past natural disasters provided little guidance.

2. The Narrative of Beneficial Learning from Natural Disasters

In order to develop our argument regarding the dangers of learning from disasters, we first of all present the case for beneficial learning in this section. Social scientists argue that governments and citizens have learned three important lessons and that these lessons reduce disaster mortality. First, disaster prevention and mitigation is possible. Second, mitigation suffers from collective action problems that can best be solved by public disaster preparedness policies. Yet, and this is the third lesson, knowledge that public policies are required does not automatically imply that governments invest sufficiently in these policies. Governments only act if citizens can hold them accountable

for insufficient supply of disaster preparedness, if governments are responsive and have sufficient financial resources at their disposal.

Until the age of enlightenment, humans perceived natural disasters as acts of god or gods and thought that disasters either are a punishment for humans' sins or instruments chosen by gods to remind humans of the superiority of gods. Where disasters are perceived as acts of god, disaster prevention appears to be futile at best and – at worst – may trigger the wrath of gods. Indeed, investment in disaster prevention and mitigation requires faith in the effectiveness of these measures. The Lisbon earthquake and subsequent tsunami on All Saints Day in 1755 may well be the first major European disaster that was interpreted as an 'act of nature' rather than an act of god. Though theologians claimed that the earthquake was a manifestation of divine judgement, most people rejected this traditional interpretation not least because the quake destroyed almost all churches but damaged Lisbon's red light district only lightly (Paice 2008).

Over time, the emphasis shifted further and further toward human responsibility. Disasters stopped being an act of nature, let alone an act of god, over which human beings exert no influence. According to Ted Steinberg (2013), "calling a disaster an (…) *act of nature* is a distraction. It is a result of poor planning and a lack of preparation." The World Bank and the United Nations reach the same conclusion. As a recent study by the organizations suggests, "death and damage do not primarily result from geological hazards" (World Bank and United Nations 2010: 1). Instead, disasters are acts of "omission and commission" (ibid.) with the World Bank concluding that "disasters expose the cumulative implications of many earlier decisions, some taken individually, others collectively. (…) Prevention is possible (…) [though] many measures – private

and public – must work well together for effective prevention." (World Bank and United Nations 2010: 1-2). In other words, natural hazards only turn into disasters if people are exposed to the hazard and are not resilient to fully absorbing the impact without damage to life or property (Schwab et al. 2007; Paul 2011).

What we call natural disasters are therefore in fact human-made or at least human-allowed disasters since hazards only turn into disasters where humans have made insufficient efforts at prevention, mitigation, preparation and adaptation. Humans are not just victims but directly influence the social and economic consequences of natural disasters through their decisions. Therefore, learning from past disasters, understanding their causes and consequences in order to prevent or mitigate against future disasters is the main influence on disaster mortality that humans can exert. The more disasters appear to be man-made, the larger the extent to which mankind can mitigate disaster risks and prevent disaster morality.

Individuals can best avoid natural disasters by not settling in areas and regions that have a high disaster propensity. Given this is sometimes impossible and where possible is usually unattractive,[3] disaster prevention typically requires the solution of collective action problems. At the very least, collective disaster mitigation measures are more efficient and often more effective, too.[4] Private individuals underinvest in disaster

3 Properties and land in high-risk areas are either cheaper or settlement in such areas provides extra amenities such as access to the sea or an undisturbed view of the coastline.

4 Dutch water boards, which go back to the 13th century, are among the first instances where individuals jointly tried to solve collective action problems by implementing draconic punishments for the individuals whose portion of the dyke proved to have been the weakest link. In Germany, at the same time, the Sachsenspiegel tried to enforce the rule that villagers who do not safeguard their part of the dyke will lose their land. Both the Dutch water boards and the Sachsenspiegel are based on the insight that a dyke is only as good as its lowest and weakest part.

mitigation for three main reasons. Firstly, such measures are costly.[5] Secondly, many individuals neglect or ignore the probability of disasters altogether (Hough 2010), consistent with more general evidence that individuals often ignore potential impacts that come with very small probability, unknown size and unknown timing (Camerer and Kunreuther 1989; Kunreuther 1996). Thirdly, some of the devastation will affect not individuals directly exposed, but others in the wider sub-national region or even the entire country. Large-scale disasters cause significant collateral damage and macroeconomic distortions that impact the wider population (Lall and Deichmann 2010; Hallegatte and Przysluski 2011). Only governments can internalize these costs that private individuals will ignore.

Governments can tax citizens and can therefore easily overcome and resolve collective action problems and provide public goods. There is little doubt that by implementing a full battery of public disaster prevention, mitigation, preparation and adaptation measures (called public disaster preparedness policies for short below), governments can minimize loss of lives and economic damage if a hazard strikes. A loss minimizing political response to disaster risk would optimize policies on various levels: land-use plans that prevent settlements in high risk areas, public investment into dams and tsunami walls, public investment in rescue infrastructures such as shelters and early warning systems, publicly funded disaster response training, strict regulations for public and private buildings and infrastructure, and public investment in emergency services and their technology.

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5 For examples, earthquake-proof construction increases the building costs by at least 10 per cent (Kenny 2009), and a private dyke around the property or an artificial building elevation is very expensive.

Given the over-riding importance of public disaster preparedness policies, the quality of governance arrangements and the resource constraints governments face will impact on whether and to what extent actual governments follow a loss-minimizing strategy. Responsive and accountable governments spend significantly more on disaster protection and mitigation measures than less responsive and less accountable governments. Even the allocation of food aid after and during disasters is more efficiently organized when governments strive for voters' support and re-election (Neumayer and Plümper 2009). Richer societies are not per se protected from natural hazards, but richer societies build to higher standards, invest more in protective infrastructure, and can more effectively provide medical and food aid and clean drinking water after the disaster has occurred (Kahn 2005; Anbarci et al. 2005).

In sum, human beings have learned that not the occurrence of natural hazards but their consequences are strongly influenced by human impact, that disaster preparedness measures are best and most efficiently organized at the societal level, so that governments and public administrations become the obvious agents for financing and providing disaster mitigation infrastructures and early-warning systems or at least regulating, implementing and enforcing disaster-proof construction of private properties.

Empirical studies support the case for the beneficial effects of learning from disasters. For example, in Keefer et al. (2011) we show that earthquake propensity – being located on very active fault lines and therefore experiencing frequent earthquakes – reduces earthquake mortality in a global sample, holding the strength of quakes and

population density constant,[6] while in Neumayer et al. (2014) we demonstrate that higher disaster propensity also reduces economic damage from the top three disaster types, namely earthquakes, floods and tropical cyclones, which together account for roughly 70 percent of total worldwide economic damage from natural disasters. Similarly, Hsiang and Narita (2012) find that countries frequently hit by tropical cyclones experience lower human and economic loss. Hurricane experience in the past ten years lowers subsequent hurricane damage in US counties (Sadowski and Sutter 2008). Individuals and, more importantly, governments learn from past disasters to invest in disaster prevention, preparedness, mitigation and adaptation. Brody et al. (2009) point toward improvements in local flood mitigation policies after historical flood events in Florida.

There is therefore ample empirical evidence to support the view that private and public agents have learned how to reduce disaster mortality and economic damage. Yet, that disaster preparedness measures work well on average does not mean that they reduce the number of fatalities in all cases. In fact, in some cases learning from past disasters can prove disastrous and can severely increase the death toll, as we will show in the remainder of this article.

3. Potentially Fatal Lessons Learned from Public Disaster Preparedness Policies

Given the standard narrative of beneficial learning from past disasters, how can it be that almost 16,000 people died and another 2,500 people went missing in a country whose central and local governments invested more than any other country into public

6 Conversely, very little learning seems to take place where disasters are rare events (Schad et al. 2012) or happen only at the local level (Voss and Wagner 2010).

disaster preparedness policies? In this section and the next, we discuss the Tohoku events that led to what seems a surprisingly high human toll from the perspective of potentially fatal misperceptions of the affected population. These misperceptions – that is our major argument – did not occur randomly but rather have been learned by many as the result of Japanese disaster preparedness policies and individual experience. Of course, populations are heterogeneous in respect to learning. We therefore do not argue that nobody responded appropriately to the Tohoku quake and tsunami. Rather, we argue that given the frequency with which tsunamis occur in Japan, it is seemingly surprising that so many citizens failed to respond adequately in the time between the first tsunami warning and the wave hitting the Japanese shores when this time would have been sufficient to reach safety either on hills or inland.

We stress the importance of two lessons that the Japanese population did not fully learn. The first lesson is that no government investment in disaster preparedness policies and infrastructures will withstand all hazards. Governments face budget constraints and they need political support of the population to win elections. They therefore do not only have incentives to provide publicly visible disaster preparedness measures, at the same time they also face strong incentives not to invest 'too much' in these measures. Politicians cannot predict the future and therefore can neither know the timing nor the magnitude of coming disasters. Governments therefore need to choose the level of disaster mitigation policies under uncertainty. Naturally, this leads to political conflict about the optimal response. A compromise will be struck between those who want to react a lot even though the economic and, potentially, the political costs will be high and those who believe that no major disaster will occur in the foreseeable future and disaster preparedness measures can remain modest.

As a consequence, governments implement disaster preparedness policies which withstand some and perhaps the majority of hazard events, but they will never provide protection against all, or even the stronger hazards. Not even democratically elected, responsive and accountable governments in high-income countries and high disaster propensity locations will be willing to invest in policies that provide full safety from natural disasters. In addition, even if they wanted to it is difficult for policy makers to provide early warning systems and infrastructures that are guaranteed to protect the population from disaster. What is safe for 99 per cent of hazard events can fail when the 'big one' arrives.

The next section provides evidence that the second lesson the Japanese population failed to learn is to mistrust their own experiences. The fact that individuals have seen and survived the occasional mild tsunami does not imply that all tsunamis are comparably harmless. Many of the people affected by the 2011 tsunami had learned from their own previous tsunami experience or that of their parents that tsunamis reach heights that stay below the height of the tsunami walls, that not much time passes between the quake and the ensuing tsunami, that tsunami warnings issued by public agencies are usually false alarms, and that even moderately elevated parts of the town or village are safe from the tsunami run-up.

3.1. Disaster Preparedness in Japan Before the 2011 Tsunami

If there is a single country that has learned to cope with natural hazards, it is Japan. The Japanese government has arguably institutionalized disaster preparedness policies more than any other government. The country is second to none in respect to dealing with earthquakes. Japanese earthquake policies date back to the Great Kanto quake in

September 1923 which hit Japan's major industrial cities of Tokyo and Yokohama, killing well over 100,000 people. According to undisclosed sources, the damage to Tokyo was so large that the government considered moving the capital to another city (Schencking 2013). Yet, the government took the opportunity and replaced destroyed buildings with modern concrete and steel buildings that were designed to be quake-proof or at least quake-resistant.

Since the country resides on some of the most active fault lines in the world, government agencies, especially Japan's Meteorological Agency, carefully monitor seismic activities and are able to issue an earthquake warning within seconds after a shockwave is recorded. The agency controls more than 4,000 seismometers and is able to predict the expected epicentre of an earthquake even before the tremors reach affected prefectures. The Agency is not just responsible for earthquake warnings but also issues tsunami warnings.

Japan's modern disaster mitigation policies rest on four pillars: i) an extremely strict building and construction code which is regularly updated and strengthened, ii) a strict earthquake drill system in schools and public and private institutions,[7] iii) a sophisticated early warning system, which relies on sensors that record all seismic activities on the islands and off-shore, and iv) a system of earthquake- and tsunami-resistant shelters, floodgates and tsunami walls.[8] With the exception of the building and construction regulations and the early warning system, these policies are implemented,

7 Households are required to keep a 'survival kit' with clean drinking water, food for a few days, a radio, a flashlight, and a first aid kit. Pupils are also trained to seek safety under tables or in doorframes should an earthquake occur.

8 Tsunami protection infrastructure consists of multiple structures, including breakwaters, vertical concrete flood walls, compacted earth tsunami barriers, and sluice gate structures, among others (Chock et al. 2013). We often refer to this infrastructure simply as sea walls.

financed, and administered at the prefecture level (World Bank 2012). Prefectures invest in tsunami walls and shelters, they finance public hospitals, and they organize annual earthquake drills.

In one sentence, Japan was very well prepared for earthquakes and tsunamis.

3.2. The 2011 Tohoku Quake and Tsunami: an Unexpectedly Strong Hazard Event

Japan was prepared, but the strength of the event when it occurred on Friday 11th March 2011 still took the population and the public authorities by surprise. The Tohoku quake was an event of magnitude 9.0 on the Richter scale – the strongest earthquake ever recorded in Japanese history. According to Takeshi Koizumi, one of JMA's senior coordinators for international earthquake and tsunami information, the JMA "had not expected a 9-plus magnitude earthquake."[9] The major tremor stroke at 14.46 JST and had its epicentre at 38.322°N and 142.369°E, which is a point approximately 70 kilometres off the Japanese East Coast. The quake lasted for six minutes. It triggered a tsunami which reached the Japanese East Coast at 15.12 JST and thus less than half an hour after the quake.

3.3. Flaws in the Early Warning System and Other Public Preparedness Measures

The JMA quickly responded to the seismic information it received and issued an earthquake and tsunami warning three minutes after the earthquake at 14:49 JST. The first warning severely underestimated the height of the run-up waves. It rated the expected tsunami as "major" – the highest scale – but predicted that the tsunami would

9 http://www.telegraph.co.uk/news/worldnews/asia/japan/9920042/Tsunami-two-years-on-Japan-finally-gets-warning-system-that-would-have-saved-hundreds-of-lives.html

only reach 6 meters in Miyagi, 3 meters in Iwate and Fukushima, and 2 meters in Ibaraki and Chiba prefectures. The first warning was modified 25 minutes later, at 15:14 JST. In the updated warning, the JMA corrected the estimates tsunami height to 10 meters for Miyagi coast and to 6 meters for Iwate and Fukushima.

It was not before 15:30, however, that the JMA's tsunami predictions became reliable. At this time, the forecasts were based on global seismic data which indicated a much larger earthquake and therefore much higher waves.[10] In actual fact, the tsunami reached a height of up to 10 meters. Much more important than tsunami heights are run-up heights, however, that is, how far above sea level the turbulent surge of water choked with debris rises. Run-up heights in Chiba, Fukushima, Ibaraki, Iwate, and Miyagi reached 8.13 meters, 21.01 meters, 9.65 meters, 40.57 meters, and 34.74 meters, respectively.

Post-disaster investigations identified five important flaws in the JMA's early warning system and in other public preparedness measures:

First, initial estimates of the earthquake were imprecise, but the JMA calculated and published the resulting tsunami height as if the predictions had been precise. Since the quake was stronger than initially assumed, the actual wave height was underestimated. This problem was exacerbated by the fact that historically JMA's warnings tended to suffer from the opposite problem: predicting higher waves than occurred, "thus creating a misperception that an actual tsunami would always be much smaller than the one predicted by official warnings" (Hasegawa 2013: 19).

10 Information based on Japan Meteorological Agency (2013).

Second, the highest scale 'major tsunami' already begins at fairly low levels and the label 'major tsunami' does not sound urgent enough. 'Potentially devastating' would have been a better name for the highest category.

Third, tsunami warnings are issued in 'estimated wave heights' which may fall dramatically short of run-up heights. Given tsunamis are very low frequency events, it is unclear whether Japanese individuals have learned the difference between tsunami height and run-up height, including the fact that run-up heights can exceed wave heights by factor 4 or 5.

Fourth, in many municipalities public loudspeakers were used to disseminate the tsunami warning but the earthquake destroyed these in some municipalities, leaving individuals to learn about the event via other means (Hasegawa 2013: 16). Of course, given that the first warning was potentially misleading, it remains unclear whether not being informed about the expected wave height was an advantage or a disadvantage.

Fifth, Japanese municipalities frequently conduct evacuation drills, which seek to train the behaviour after earthquakes. A central element of these drills is evacuation to pre-defined gathering points. These points are safe from collapsing buildings, thus optimised for the low frequency event of earthquakes, but not optimised for the very low frequency event of tsunamis. In many affected municipalities, evacuation points were close to rivers and therefore prone to flooding. While the earthquake destroyed a few buildings, most infrastructures remained intact and were only destroyed by the tsunami. Likewise, only few were killed by the earthquake itself – the tsunami killed the vast majority of victims.

3.4. The False Notion of Safety Generated by Tsunami Walls and Shelters

It is not possible to estimate the mortality impact of the Tohoku tsunami in the counterfactual scenario that the JMA would have correctly predicted that the height of the tsunami reached 10-15 meters in most coastal parts and run-up heights of up to 40 meters. In most prefectures, the time until the tsunami washed over the tsunami walls would have allowed the vast majority of people to flee far enough inland or to higher ground to be safe.

What proved fatal for many, however, was not the JMA's initial flawed tsunami warning as such, but its combination with the existence of tsunami walls and shelters which tempted many citizens into staying close to the coast, watching the incoming wave, taking pictures and shooting short movies with their cell phones instead of fleeing further inland or to higher ground. According to an official study published by the Japanese government in August 2011, only 58 per cent of people tried to reach higher ground in Miyagi and Fukushima (Oskin 2015). Another study into the post-Tsunami disaster evacuation points the finger squarely at the moral hazard problem that comes with Japan's otherwise outstanding disaster preparedness policies: "[T]he fact that these coastal towns had 5–10 m breakwaters built along the coast for protection against the inflow of tsunami waves further delayed the residents' decision to flee. One evacuee from Ofunato City said: 'When I first heard a tsunami warning for 3 metres, I thought that it would be all right because the breakwater in our town is higher than that.' (…) In reality, the tsunami that hit the three prefectures had a 10–15 m mean inundation height and a 40 m run-up height in some places. (…) As a result, despite the early tsunami warning, many residents were caught by surprise when the actual tsunami arrived." (Hasegawa 2013: 15-16).

With the predicted wave heights of the tsunami warning being too low, the walls (and shelters too) lured many staying behind believing the wall would shield them and, failing that, the shelters would be safe. In actual fact, the walls were not high enough and the shelters were often not safe given the strength of the tsunami event. A good example for this is the municipality of Kamaishi, a hilly city in which rescue would have been immediate and complete if only all citizens had chosen to run uphill. Instead, many stayed behind expecting that its tsunami breakwater system, completed only three years prior, would provide adequate protection (New York Times 2011b). For 884 of its inhabitants that expectation proved fatal.

3.5. The False Notion of Safety Generated by Hazard Maps Derived from Past Disasters

A similar problem arose from public zoning of areas supposed to be of low or no risk of inundation. Many municipalities had hazard maps in place that marked out zones at risk and on the basis of which evacuation drills were organised. These maps were based on learning from past tsunamis but hugely underestimated the areas at risk for a mega-event like the 2011 tsunami. The maps left those residing outside the apparent risk zones in a false sense of security and in the belief that there was no need for evacuation when the tsunami warning came (Hasegawa 2013: 18).

3.6. Discussion

The Tohoku tsunami amply demonstrates the double edged sword of learning from past disasters. On the one hand, learning can be argued to have been beneficial. The early warning system that Japan has in place is the learning consequence from previous disasters and if we compare the actual tsunami warning to a situation without any

warning, the warning definitely saved lives.[11] Similarly for the system of tsunami walls and shelters: In comparison to a situation in which no tsunami wall existed *and* no warning was issued, the walls probably saved lives.

Yet, on the other hand these learning achievements from past disasters proved disastrous since the worst case occurs when people feel safe behind and inside protective infrastructures that eventually fail. The existence of tsunami walls and shelters in combination with the underestimation of the wave height by Japan's Meteorological Agency strongly exacerbated the tsunami death toll.

4. Potentially Fatal Lessons Learned from Experience

Not only public disaster preparedness policies can induce a false sense of security; misleading individual experiences can also contribute to the impression of a lack of urgency and delay or prevent adequate individual responses. Just like government agencies were taken by surprise by the strength of the natural hazard, many individuals too were not prepared for the 'big one'. People living on Japan's East Coast had no experience with earthquakes and tsunamis of the Tohoku magnitude. All tsunamis they had experienced over their lifetime were smaller, and often much smaller.

In addition, previous earthquakes that had triggered tsunamis had a location closer to the Japanese shore. As a consequence, most previous tsunamis had arrived on-shore about 15 minutes after the earthquake. The Tohoku earthquake was caused by plate tectonics further off-shore, which had the consequence that the wave took at least 30 to 40 minutes to reach the Japanese Eastern shore. 15 minutes after the tsunami warning

11 One of the reasons for the extremely large death toll of the 2004 tsunami in the Indian Ocean was that there were either no or very poor early warning systems in place.

many people who had fled to higher areas thought that a false alarm had been activated and returned to lower ground – often reaching the coast when the tsunami arrived (Hasegawa 2013: 19). They had learned a lesson from past tsunamis that proved fatally wrong for the 2011 tsunami.

Accordingly, this suggests that prior experience with tsunamis may have prompted a wrong reaction to the tsunami warning. This section adds further evidence of the potential dangers of learning from experience based on a statistical analysis of mortality in municipalities affected by the Tohoku tsunami. We demonstrate that municipalities which had previously experienced actual tsunami mortality suffered fewer fatalities in 2011 than municipalities which had experienced previous tsunamis that remained moderate and did not take lives. We interpret this result as evidence for the argument that individuals can falsely learn that tsunamis are relatively harmless (also keeping in mind the existence of tsunami walls).

4.1. Research Design

Our unit of analysis is the municipality and our measures of experience that individuals living in a municipality will have had and from which they could have learned refer to the tsunami experience in these municipalities since the last major tsunami hit Japan in 1933. There have been other more minor tsunamis but the one from 1933 was the last major one and the only major one in living memory, i.e. the only one that some people who were still living in 2011 had personally experienced. The next significant tsunami further back in time occurred in 1896.

Our first measure of past experience is the maximum wave height of previous tsunamis on the shore of the municipality. Ideally, we would have liked to use information on run-

up height rather than wave height for historical tsunamis but unfortunately this more directly relevant information has far too many missings for historical tsunamis. Only for the 2011 tsunami is there almost complete information on run-up heights. Our second measure is the sum of people that died in a previous tsunami in that municipality. A sum total of 3,100 people have died from tsunamis since 1933 in the municipalities in our sample. Our two measures of past experience are correlated with each other but not very strongly (r = 0.35).

We analyze Tohoku tsunami deaths per municipality.[12] We obtained run-up information for tsunamis in Japan from the National Geophysical Data Center/World Data Service Global Historical Tsunami Database (NGD/WDS).[13] For each run-up, the database includes, among other characteristics of the specific overland flow, geographical coordinates, maximum water height above sea level (run-up height), distance from source (the epicentre of the quake), and most importantly, casualties. The coordinates of each run-up were assigned to a municipality using the boundary shapefile from the Global Map Japan version 2.1 at the Geospatial Information Authority of Japan.[14] The run-ups that could not be assigned to a municipality polygon in this way were matched to municipalities manually for cases with tsunami-related deaths in 2011 or by nearest distance to a polygon centroid for other cases.

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12 There are 1,741 municipalities in our municipality shapefile of 2015. We are interested in municipalities where people could have plausibly been killed by the Tohoku tsunami and therefore we eliminated all municipalities with run-up heights below 1 metre. That leaves 88 municipalities with a record of 15,392 deaths in 2011. Our results are robust to restricting the sample to municipalities which experienced even higher run-ups of above 2.87 metres, which is the lowest run-up height in municipalities where people died in 2011.

13 http://www.ngdc.noaa.gov/hazard/tsu_db.shtml. This tsunami catalogue has been confirmed as complete (Geist and Parsons 2011).

14 http://www.gsi.go.jp/kankyochiri/gm_japan_e.html.

We control for run-up heights and distance in kilometres from the location of the Tohoku quake (which is indicative for the time between the first tsunami warning and the arrival of the tsunami wave).[15] The maximum height of the tsunami run-up varies from 1.19 to 40.57 metres in the municipality of Miyako. The two measures are negatively correlated at r = -0.59. We tested for an interaction effect between the two measures as well as for non-linear effects of both measures but found no evidence that these represent better fitting models based on Akaike and Bayesian Information Criteria. These more complex models also hardly change the predictions from the simpler baseline model.

In addition, we control for a number of socio-economic factors that may explain variation in mortality at the aggregate municipal level. Specifically, we include the (log of) the total population in a municipality, the share of people older than 64, the share of people who have completed up to a senior high school degree, the share of people in employment and an index of the financial strength of a municipality.[16] Municipal statistics were obtained from the Regional Statistics Database at the Portal Site of Official Statistics of Japan, Statistics Bureau, Ministry of Internal Affairs and Communications.[17] See the Appendix for summary descriptive variable statistics.

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15 It is only a proxy variable because the time between the outbreak of the earthquake and the first wave hitting the shore is not only determined by geographical distance but also by ocean depth and bathymetry, coastal characteristics and other factors.

16 The financial strength index was obtained for 2012, while all other socio-economic variables were obtained for 2010.

17 https://www.e-stat.go.jp/SG1/chiiki/Welcome.do. Municipal statistics correspond to municipalities existing in March 2014 while the shapefile municipality polygons correspond to municipalities existing in January 1, 2015. This is the best possible match of municipality boundaries given the Japanese government's policy of municipality mergers and availability of municipality covariates. The assignment of municipality coordinates to the municipality polygons of 2011 (Global Map Japan version 2) produced the same match as with the 2015 polygons.

Our dependent variable is the count of Tohoku fatalities, for which the variance is greater than its mean. Due to this over-dispersion we use a negative binomial rather than a Poisson estimator. Standard errors are clustered on the 10 prefectures in which the 88 municipalities are located.

4.2. Estimation Results

We start with a model that does not include socio-economic variables other than population size (model 1). The two natural hazard strength measures and population size have the expected effects. The reported coefficients can be interpreted as semi-elasticities. For example, each additional metre of run-up height is estimated to increase the death toll by approximately 9 percent. Model 2 adds the other socio-economic variables, whereas model 3 additionally includes prefectures fixed effects to account for some unobserved heterogeneity across the 10 prefectures in which the 88 municipalities lie. The estimated effects for our hazard and learning variables are fairly stable and therefore robust. The financial strength of a municipality has the expected negative effect. Better off municipalities can afford better mitigation policies. Surprisingly, the educational attainment level of the population in a municipality has a positive effect and the share of elderly people has no consistent effect. [18] The elderly are less physically mobile but also have more tsunami experience such that the two effects go into opposite directions. It is unclear to us why municipalities with better educated populations suffered higher fatalities.

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18 Of course, our quantitative analysis cannot and does not aim at the individual predictors of disaster mortality. Only individual-level data could explain why some individuals stayed in low elevation areas until the tsunami flooded over the tsunami walls while others left the coastal area immediately after Japan's Meteorological Agency issued a tsunami warning, however imperfect it was, and why many individuals searched safety in tsunami shelters, while others ran for nearby hillsides.

Table 1. Determinants of mortality in the 2011 tsunami.

	Model 1	Model 2	Model 3
maximum run-up height	0.0901	0.0952	0.0949
	(0.0392)	(0.0290)	(0.0472)
distance to quake epicentre	-0.0262	-0.0304	-0.0245
	(0.00184)	(0.00493)	(0.0114)
sum of historical tsunami deaths	-0.00227	-0.00211	-0.00262
	(0.000572)	(0.000404)	(0.000621)
maximum historical wave height	-0.0359	-0.0179	-0.0264
	(0.0388)	(0.0201)	(0.0224)
ln population	0.669	1.119	1.354
	(0.306)	(0.213)	(0.313)
employment share		28.42	37.03
		(19.68)	(30.66)
financial strength index		-2.490	-2.262
		(0.967)	(1.070)
educational attainment		12.34	16.98
		(4.026)	(5.372)
share of older people		0.740	-2.400
		(8.998)	(10.38)
Observations	88	88	88

Note: Dependent variable is number of people killed by Tohoku tsunami in a municipality. Model 3 includes prefecture fixed effects. Standard errors adjusted for clustering on prefecture level in parentheses.

4.3. The Effects of Learning from Historical Tsunami Experience

To provide a more substantively meaningful interpretation for our main variables of interest – our two learning measures – we report predicted deaths varying the values of one learning variable and keeping all the other variables at the values as observed in the sample.[19] This analysis of substantive effects demonstrates that only the sum of historical tsunami deaths has a strong effect that is estimated with sufficient precision, whereas maximum historical wave height has a weak effect that is estimated with huge uncertainty around it.

19 We base this analysis of substantive effects on model 1 but results are similar for basing the analysis on models 2 or 3.

Starting with the latter, where historically there has been no tsunami experience, the predicted mortality in the 2011 tsunami is 315 [90% confidence interval: 9; 933],[20] falling to 283 [49; 516] fatalities at the median historical wave height of 3 metres, 259 [75; 443] fatalities at the 75th percentile (equivalent to 5.45 metres) and 198 [96; 299] fatalities at the 95th percentile of wave height (equivalent to 13 metres). Note that the confidence intervals are very large. We infer from this that individuals do not seem to have systematically learned from historical experience with tsunami heights in their municipality. Municipalities with higher historical waves do not systematically experience lower mortality in 2011.

Things are different for our second information from which individuals can learn. Because of the skewed nature of the historical deaths variable – only 7 out of the 88 observations experienced such tsunami fatalities since 1933 – we assess percentiles across the range of strictly positive values of this variable only. At the median of positive values (69 historical deaths), the predicted mortality is 225 [89; 361], falling to, respectively, 30 [13; 47] and 6 [0; 13] fatalities at the 75th and 90th percentile (representing 957 and 1,678 historical deaths, respectively). We interpret this as evidence that where historical experience suggests that tsunamis can kill substantial numbers of people, some individuals have learned the right lesson and predicted mortality is therefore systematically lower in these municipalities than in municipalities where experience comes from tsunami waves without fatalities.

As mentioned, only 7 of the 88 municipalities experienced historical tsunami fatalities. Of these, 4 municipalities had between 9 and 69 historical fatalities, whereas 3 others stand out, having suffered from very substantial fatalities: Ofunato with 344, Miyako

20 Just below 10 percent of cases in our sample fall into this category.

with 957 and Fudai with 1,678 deaths. To check the robustness of our predictions, we excluded each one of these municipalities at a time. We find that results are relatively stable and are therefore not driven by any one of these three municipalities in the sample.

4.4. The Fudai Case

The Fudai case is of particular interest since, firstly, no one died in the 2011 event and, secondly, potential beneficial learning by individual citizens was accompanied by the lessons that one particular individual drew from his own experience: Fudai's 10-term mayor, Kotaku Wamura, survived an earlier tsunami and therefore made it his personal mission to protect his city by a floodgate high enough to withstand even high run-ups (Birmingham and McNeill 2014). Despite significant opposition, works on the tsunami wall were finished in 1967 and reached a height of about 15.5 meters across a length of 155 meters. Its costs totalled 3.5 billion Yen, roughly one quarter of Japan's per capita income for each of Fudai's citizens. The floodgate was criticised as wasteful at the time it was built and thereafter, even though the construction was greatly facilitated by mountains on both sides of the dam such that the construction merely needed to close a gap between mountains (Daily Mail 2011). Though Wamura probably was not the only Japanese politician who thought that the 3 to 6-meter height tsunami walls typically built to protect other cities were not high enough, he proved to be one of few mayors popular enough to be able to afford pushing forward with a pet project that was expensive in the short run and saved lives only many years after Wamura's death. He simply did not allow others to water down his plans to build a tsunami wall much higher than in most other municipalities.

The other two municipalities with very substantial historical tsunami mortality (Ofunato and Miyako) did not escape very substantial mortality in 2011, even if our model predicts that their 2011 mortality would have been higher still without learning given the level of their exposure to the strength of the hazard.[21] Yet, it remains true that no mortality in 2011 should have occurred had the citizens of Ofunato and Miyato fully learned their lesson. At best, their learning was insufficiently consequential.

4.5. Discussion

Our findings support Hasegawa's (2013: 18) contention, based on interviews with survivors, that in many municipalities prior experience with smaller and comparably harmless tsunamis "created a feeling of reassurance with respect to risk and thus made some of the population more vulnerable". Our findings also suggest that previous experience in the municipality mattered more than the national or global experience with tsunamis. Individuals' expectations of whether their municipality is at risk of a fatal impact exerts a larger influence on behaviour than the general idea that tsunamis can be mortal, in which case we would not find that the historical experience of tsunami fatality in a municipality has an effect on mortality in this municipality in the 2011 tsunami. Of course, the dire experience of the Tohoku tsunami can for the foreseeable future change the perception of the potential dangers of maritime earthquakes and ensuing tsunamis across potentially affected locations in Japan, whether or not people died in 2011.

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21 The death toll in these two municipalities, whilst substantial, is lower than what would be predicted by their close proximity of merely approximately 99 and 152 kilometres to the epicentre of the earthquake, respectively, and the very substantial run-up heights of app. 30 and 40 metres, respectively. Setting counter-factually their experience with historical tsunami fatalities to zero allows us to calculate that around 1,500 more people would have died in Miyako and 800 more people in Ofunato had it not been for learning from historical tsunami experience.

5. Conclusion

Learning from past hazard events can have devastating consequences if individuals draw the wrong lessons from previously experienced hazard events that did not prove disastrous. The wrong lesson learnt is that public preparedness measures provide safety in all events, whereas the only thing that can validly be inferred is that they provided safety for the actual events of the magnitude experienced. Protective infrastructures and other preparedness policies cause a moral hazard problem in the broader sense – in the sense that public investment in security causes individuals to accept more risks than they should. Individuals that have previously experienced only light variants of a disaster type can learn to become careless under the spell of a false impression of safety that public preparedness measures create. The worst case of a natural disaster does not necessarily occur in the absence of such measures, but when these measures unexpectedly fail after having worked for long periods of time.

Our statistical analysis demonstrates that municipalities that experienced tsunamis without mortality over the period of a life span of a Japanese generation – about 80 years – suffered a higher death toll during the Tohoku tsunami. Or to put it differently: municipalities that previously experienced tsunami mortality suffered fewer fatalities during the Tohoku tsunami. In the absence of fatalities and therefore in the absence of demonstrable evidence that public safety measures have failed, the mere fact of having experienced waves of several metres high did not trigger a learning effect that proved beneficial in the 2011 tsunami.

The Fudai case presented in the previous section demonstrates that one influential man's learning can play a crucial role. Fudai's late mayor's heroic achievement to push through against opposition and criticism the building of a much larger wall than in

neighbouring municipalities would arguably have saved almost everyone in this municipality even if no individuals had undertaken any evacuation efforts. And yet, the correct lesson from Fudai's tsunami wall is not that perfect infrastructure protection from natural hazards is possible. Fudai happens to be located further away from the epicentre of the 2011 earthquake that caused the tsunami than many other municipalities. If we wait long enough, there will be a tsunami that floods Fudai.

Thus, the best lesson to be learned is that tsunami walls do not buy lives but time that individuals should use to save their lives. Where individuals do not use the time to flee, they can be lucky and the waves are either not high enough to breach the walls or they sweep over the walls but do not cause havoc since their major force has been broken. Or the individuals can be unlucky and they are killed, unsafe in the false sense of security that the walls bring with them.

Given the over-riding importance of individuals' expectations, it is therefore important that disaster behaviour drills avoid the notion of a maximum disaster strength based on historical experience and instead repeatedly rehearse scenarios of hazard magnitudes which in living memory have never been reached. At the same time, governments that invest in protective infrastructures and other safety measures need to make it clear to citizens that this protection only buys time, not necessarily lives. Effective and beneficial learning from past natural disasters requires individuals to heed the correct lessons from the past: safety devices are not fail-proof. Our analysis strongly supports those experts who call "for a stop to more coastline engineering, saying money should be spent instead on education and evacuation drills" (New York Times 2011a). The Japanese people, like all others living in highly prepared disaster-prone locations, need

to learn the ultimate lesson, namely that Murphy's law applies to public disaster safety measures too: they can and, eventually, will fail.

Appendix: Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Tohoku death toll	88	174.91	449.32	0	3,173
maximum run-up height	88	9.84	9.68	1.19	40.57
distance to quake epicentre	88	332.70	196.95	82	1055
sum of historical tsunami deaths	88	35.23	207.52	0	1678
maximum historical wave height	88	4.23	4.77	0	29
ln population	88	10.20	1.22	8.04	13.86
employment share	88	0.47	0.04	0.39	0.62
financial strength index	88	0.47	0.28	0.12	1.48
educational attainment	88	0.40	0.04	0.31	0.49
share of older people	88	0.27	0.05	0.16	0.39

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