

BMJ Open

BMJ Open is committed to open peer review. As part of this commitment we make the peer review history of every article we publish publicly available.

When an article is published we post the peer reviewers' comments and the authors' responses online. We also post the versions of the paper that were used during peer review. These are the versions that the peer review comments apply to.

The versions of the paper that follow are the versions that were submitted during the peer review process. They are not the versions of record or the final published versions. They should not be cited or distributed as the published version of this manuscript.

BMJ Open is an open access journal and the full, final, typeset and author-corrected version of record of the manuscript is available on our site with no access controls, subscription charges or pay-per-view fees (<http://bmjopen.bmj.com>).

If you have any questions on BMJ Open's open peer review process please email info.bmjopen@bmj.com

BMJ Open

**Long-term psychological and physical health consequences
of induced earthquakes:
The impact of gas extraction on residents in Groningen**

Journal:	<i>BMJ Open</i>
Manuscript ID	bmjopen-2020-040710
Article Type:	Original research
Date Submitted by the Author:	20-May-2020
Complete List of Authors:	Stroebe, Katherine; Rijksuniversiteit Groningen, Social Psychology Postmes, Tom; Rijksuniversiteit Groningen, Social Psychology Kanis, Babet; Rijksuniversiteit Groningen, Social Psychology Richardson, Justin; Rijksuniversiteit Groningen, Social Psychology Oldersma, Frans; Department for Statistics and Research, Municipality of Groningen, Groningen, Netherlands Broer, Jan; Municipal Health Services Groningen, ABPG; Greven, Frans; Municipal Health Services Groningen, the Netherlands, Department of Environmental Health
Keywords:	MENTAL HEALTH, EPIDEMIOLOGY, PUBLIC HEALTH

SCHOLARONE™
Manuscripts



I, the Submitting Author has the right to grant and does grant on behalf of all authors of the Work (as defined in the below author licence), an exclusive licence and/or a non-exclusive licence for contributions from authors who are: i) UK Crown employees; ii) where BMJ has agreed a CC-BY licence shall apply, and/or iii) in accordance with the terms applicable for US Federal Government officers or employees acting as part of their official duties; on a worldwide, perpetual, irrevocable, royalty-free basis to BMJ Publishing Group Ltd ("BMJ") its licensees and where the relevant Journal is co-owned by BMJ to the co-owners of the Journal, to publish the Work in this journal and any other BMJ products and to exploit all rights, as set out in our [licence](#).

The Submitting Author accepts and understands that any supply made under these terms is made by BMJ to the Submitting Author unless you are acting as an employee on behalf of your employer or a postgraduate student of an affiliated institution which is paying any applicable article publishing charge ("APC") for Open Access articles. Where the Submitting Author wishes to make the Work available on an Open Access basis (and intends to pay the relevant APC), the terms of reuse of such Open Access shall be governed by a Creative Commons licence – details of these licences and which [Creative Commons](#) licence will apply to this Work are set out in our licence referred to above.

Other than as permitted in any relevant BMJ Author's Self Archiving Policies, I confirm this Work has not been accepted for publication elsewhere, is not being considered for publication elsewhere and does not duplicate material already published. I confirm all authors consent to publication of this Work and authorise the granting of this licence.

1
2
3
4
5
6 Long-term psychological and physical health consequences of induced earthquakes:
7

8 The impact of gas extraction on residents in Groningen
9

10 Stroebe, K.¹, Kanis, B.¹, Richardson, J.¹, Oldersma, F.², Broer, J.³, Greven, F.³ & Postmes, T.¹,
11
12

13
14 1. University of Groningen, Faculty of Behavioral and Social Sciences, Groningen,
15 Netherlands

16 2. Department for Statistics and Research, Municipality of Groningen, Groningen,
17 Netherlands

18 3. Municipal Health Services Groningen, Groningen, Netherlands
19
20

21 Corresponding author: Katherine Stroebe, k.e.stroebe@rug.nl, +313636509
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Abstract

Objectives: The aim was to evaluate the long-term (psychosomatic) health consequences of earthquakes caused by gas extraction compared to a non-exposure control group. Exposure (versus non-exposure) was hypothesized to have a negative impact on (psychosomatic) health outcomes. Impact was expected to increase over time.

Setting — Large scale gas extraction in the Netherlands that induces earthquakes and considerable damage to housing.

Participants — A representative sample of inhabitants randomly selected from municipal population records was contacted 5 times during 21 months (t1:N=3934; t5:N=2156; mean age: 56.54; 50%males; 47%females)

Main (outcome) measures — (Psychosomatic) health outcomes assessed via perceived health, stress related health symptoms, mental health. Independent variable was personal exposure to the consequences of induced earthquakes - assessed via experienced damage to housing (classified into no, once and repeated damages).

Results: Exposure to induced earthquakes has negative health consequences mainly for those whose homes were damaged repeatedly. Compared to a no-damage control group, repeated damage was associated with lower perceived health (OR:1.64), mental health (OR:1.81) and more stress-related health symptoms (OR:2.52). Health effects increased over time: In terms of relative risk, by time 5, those whose homes had repeated damage were 1.61 times more likely to report poor health, 2.08 times more likely to report negative mental health and 2.86 times more at risk of elevated stress related health symptoms.

Conclusion

There are indications that induced earthquakes can pose health risks, but little is known about their long-term impact. The present study is the first to provide evidence that induced earthquakes can have negative health consequences for inhabitants. It identifies which subpopulation is particularly at risk and why. These findings can have important implications for the prevention of negative health consequences of induced earthquakes.

1
2
3
4
5 Keywords: induced earthquakes; seismicity; longitudinal; psychosomatic health, gas extraction
6
7

8 **Strengths and limitations**

- 9
- 10 ● The long-term impact of induced seismicity is not well documented despite
11 concerns about potential health risks thereof. The present study employs a
12 longitudinal panel design to study the health consequences of those exposed to
13 the consequences of induced earthquakes compared to those not-exposed.
14
 - 15 ● The present study provides first time evidence that gas extraction that causes
16 induced earthquakes poses severe and long-term (psychosomatic) health risks. It
17 stresses the vulnerability of exposed populations and can provide important input
18 for future decision making, monitoring and contingency planning.
19
 - 20 ● Younger respondents were somewhat underrepresented in our sample and there
21 was attrition over time. However, attrition was no different for the exposed and
22 non-exposed groups, unrelated to health outcomes, and all further analyses
23 suggest that neither attrition nor sample characteristics had any substantial
24 influence on results and conclusions drawn.
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

INTRODUCTION

Recent years have seen a rise in induced seismicity due to human activities such as fracking, mining or gas extraction. This development is expected to continue. While smaller in magnitude than natural seismicity, induced seismicity can expose populations to considerable physical (e.g., damage to housing) and social risks (e.g., conflicts between residents and institutions). Moreover, this exposure is recurrent and chronic over time. While there is some insight into the long-term health risks of naturally occurring seismicity, little is known about the impact of induced seismicity. Given the increased use of energy technologies associated with seismicity, also in densely populated areas, knowledge of its health impact is important [1,2].

Naturally occurring seismicity is associated with mental health problems in survivors (e.g., depression, PTSD)[3,4]. These studies are generally cross-sectional and lack an unexposed control group [3]. Moreover, the impact of natural- cannot be equated with that of induced- seismicity for several reasons: Systematic reviews suggest there is *lower* prevalence of mental health impairment for natural compared to human/technological disasters[5,6]; but see [7]. Additionally, different stressors are at play: Natural seismicity can be of greater magnitude, causing death and extensive damages to buildings. For induced seismicity, the maximum magnitude of earthquakes tends to be smaller [8,9]. Risks involve damage to property and an incremental impact on health, as residents are exposed to long-term stressors (e.g., damages; changing community relations; conflicts of interest with powerful institutions [10,11]).

Factual information regarding the health impact of induced seismicity is sparse. Cross-sectional self-report studies([12-14] and an evaluation of health records of

1
2
3 exposed adults[15] in the context of unconventional gas extraction, suggest
4
5 associations between induced seismicity and increased (psychosomatic) health
6
7 symptoms (e.g., sleep disruption, headaches, stress). It is difficult to draw conclusions
8
9 regarding the impact of seismicity from such studies: Exposure to (the consequences
10
11 of) seismicity is not distinguished from other risk factors (e.g., wastewater injections).
12
13 Additionally, most studies lack a non-exposed control group and thus a reliable baseline
14
15 comparison. None we are aware of consider the longitudinal effects of exposure.
16
17

18
19 This lack of information regarding the (long-term) impact of induced seismicity
20
21 on health is problematic. The occurrence of induced earthquakes is increasingly
22
23 common across the globe, 1174 projects worldwide report induced seismicity [16]. High-
24
25 profile cases of induced earthquakes have occurred in Oklahoma, U.S.A., and (on a
26
27 smaller scale) Lancashire, UK [17,18]. There are rising concerns regarding the
28
29 consequences thereof within exposed populations, coupled with calls to policy makers
30
31 for monitoring and contingency planning[17]. Policy makers need to weigh the wider
32
33 economic (and sometimes environmental) benefits against potential drawbacks for
34
35 exposed residents[19].
36
37
38
39

40 The present work was designed to address the lack of information regarding the
41
42 long-term impact of induced seismicity for residents: It studies the longitudinal
43
44 (psychosomatic) health impact of induced seismicity on a group exposed to the
45
46 consequences of seismicity (damage to housing) versus a control group not exposed to
47
48 these consequences. The present study is novel in charting the chronic impact of
49
50 exposure to damage on health over a time period of almost two years, on a large
51
52 sample. We tested the following hypotheses: 1. Exposure versus non-exposure will
53
54
55
56
57
58
59
60

1
2
3 have a negative impact on (psychosomatic) health outcomes. 2. Increases in exposure
4 are related to poorer health outcomes.
5
6
7

8 9 **METHOD**

10 11 12 13 **Setting and exposure**

14
15 The study was conducted in the province of Groningen, Netherlands, where
16 conventional gas extraction from the largest gas field in Europe takes place. Exposed
17 residents experience rising concerns about physical safety, loss of property value and
18 uncertainty about the future[20,21]. The benefits of extraction flow to the operator (the
19 Netherlands' petroleum company) and the national government, while damage repair
20 and compensation by these entities has been criticized as being inadequate [20].
21
22
23
24
25
26
27
28
29

30 Seismicity has increased over time. While the magnitude of seismic events (up to
31 3.6 Richter) is generally considered 'light', their impact is felt well beyond the gas field
32 boundaries. Also, multiple factors (limited depth & high rates of occurrence of
33 earthquakes; surface constitution) contribute to considerable damage to housing in a
34 region not prepared for seismic activity [22]. For these reasons, documented damage
35 has proven the most proximal measure of exposure, compared to indicators of
36 seismicity [23].
37
38
39
40
41
42
43
44
45
46
47

48 **Sample and recruitment**

49
50
51 A stratified random sample was drawn of 25000 residents of the province of Groningen,
52 aged 16 and over, from the official municipal population records which is a complete
53 register of all legal residents. Sampling occurred in areas where damage is reported
54
55
56
57
58
59
60

1
2
3 and from outlying areas where this is not the case. Postal-code areas that were rural
4 and strongly affected by damage were oversampled¹. Participants received letters with
5 personal login codes and one reminder. Eighteen percent signed up. Baseline
6
7
8 equivalence of non-exposed groups and exposed groups was assessed. Differences
9
10
11 between groups were significant but small. Those with multiple damage to homes were
12
13
14 slightly younger ($r^2 = .014$), more highly educated (Cramer's $V = .062$), and more likely to
15
16
17 be male ($V = .072$). The first two characteristics suggest the exposed group might be
18
19
20 slightly healthier. We statistically controlled for these characteristics.
21
22

23 Data sources

24 Procedure

25
26
27
28
29
30
31 Questionnaires were sent via an email link or by post. A reminder was sent after 2
32
33
34 weeks. Participants (t1: N=3934; t5: N=2156) completed measures at 5 time points
35
36 during 2 years (T1: February 2016, T2: June 2016; T3: October 2016; T4: April 2017;
37
38 T5: October 2017; see Table 2).
39
40
41

42 Study Variables

43
44
45 *Exposure to consequences of gas extraction* was operationalized in two ways. Physical
46
47 exposure to ground motion was assessed by calculating the cumulative peak ground
48
49 acceleration (PGA_{cum}) on the basis of “shakemaps” provided by the Dutch geological
50
51
52

53
54
55 ¹ In the Netherlands, 4-number postal-code areas provide reasonably accurate geographic positioning,
56
57 whilst preserving anonymity. Data about damage in each area was provided by the institution handling
58
59 damage claims, the Centrum voor Veilig Wonen.
60

1
2
3 survey (KNMI)². Personal exposure to damage due to gas extraction was assessed by
4 asking participants to indicate how often their home had been damaged (never, once or
5 multiple times)³.
6
7
8

9
10 *Demographic variables* included gender, age and education level (categorized
11 into 'low', 'middle' or 'high' level of education).
12
13

14 *(Psychosomatic) health outcomes* were assessed at (almost) all time points
15 (Table 2) as follows via:
16
17

18
19 1. The WHO and Statistics Netherlands recommended health survey item
20 assessing *self-rated health* [24] ('how good is your health in general?', from 'very poor'
21 to 'excellent' on a 5 point scale), which is part of the SF-36 [25].
22
23
24
25

26 2. *Stress-related health symptoms*, based on prior research on symptoms of
27 disaster impact [26]. This list of symptoms was shortened by authors (JB, FG, TP):
28 symptoms associated with chronic stress were retained⁴. Consequences of exposure to
29 toxic substances and noise (e.g., hearing problems) were deemed irrelevant for
30 earthquakes and removed. Ten symptoms (stomach problems, heart palpitations,
31 headaches, dizziness/lightheadedness, sensitivity to light/sounds, muscle/joint pains,
32 irritability, memory/concentration problems, insomnia, tiredness) were assessed by
33 asking 'how often have you experienced the following complaint(s) in the past four
34 weeks' with response options 'never, rarely, occasionally, often, most times,
35 continuously'. Aggregate health index scores were computed for stress-related health
36
37
38
39
40
41
42
43
44
45
46
47
48
49

50
51 _____
52 ² KNMI calculates shakemaps based on motion sensor readings. For each participant, the PGA of all
53 events modelled by KNMI between 2012 and 2017 was summed, to create an index of exposure to
54 ground motion before and during the study.

55 ³ See supplementary materials (table S2) for demographic characteristics by level of damage exposure.

56 ⁴ Notably, at the level of individuals who suffer these complaints they are referred to as "medically
57 unexplained" because they can have multiple sources, among which is chronic stress.
58
59

1
2
3 symptoms, so that individuals have a score of 0 to 100, with 100 representing optimal
4 health. Psychometric properties of the aggregate scale were adequate. Correlations
5 among items ranged from ordinal rho 0.26 to 0.72 (median=0.39). A single factor
6 explained 46% of variance. Scale reliability was good with omega=.90.
7
8
9

10
11
12 3. The five item Mental Health Inventory (MHI-5), part of the Short Form Health
13 Survey (SF-36), measuring general *mental health* [25,27]. The MHI-5 has a score of 0
14 to 100. A score of 100 represents optimal mental health.
15
16
17
18
19

20 21 Data management and Analysis

22
23
24 Analyses controlled for age, gender and education level. Analyses were weighted
25 to correct for sampling effects of age, gender and degree of exposure of postal-code
26 areas⁵. The weights were developed to counteract any potential distortive effect due to
27 age composition, among others (e.g., because younger people were underrepresented,
28 see results section). We report the weighted results. The unweighted results were very
29 similar.
30
31
32
33
34
35
36
37

38 To assess the impact of exposure to gas extraction on health over time, we
39 constructed multilevel conditional growth models on the three health indices with
40 damage to housing as the (between group) predictor[28]. Participants with missing data
41 on the health indices were retained, as multilevel modelling is robust to missingness in
42 estimation of model outcomes.
43
44
45
46
47
48
49
50
51
52
53

54
55 ⁵ As mentioned, we oversampled rural areas as well as the most heavily exposed areas. The
56 geographical weighting was added to control for this overrepresentation.
57
58
59

1
2
3 Models were tested in a step-wise approach, first including control variables
4 (gender, age, level of education) and time. At the next step, physical exposure (PGA_{cum})
5 was added, followed by earthquake damage at time 1 and the increase of damage since
6 time 1. The final model included the interaction between damage and time. Model fit
7 was compared to assess which variables best predicted health outcomes. The best
8 fitting models were those including the interaction of damage by time (see Table 3).
9
10
11
12
13
14
15
16

17 To highlight the implications of the findings, we distinguished poor and good
18 health on the basis of health scores, enabling us to compute odds ratios (OR) and
19 relative risk. For mental health we used the conventional criterion of MHI < 60 as cutoff
20 [29]. For perceived health we classified “good” and “outstanding” as good health and all
21 other scale points as poor (conform international convention). For symptoms we
22 devised our own cutoff based on distributional characteristics combined with content
23 criteria: A classification of < 60 as poor health resulted in 9% of the unaffected
24 population being classified as such. Odds ratios were calculated in weighted models,
25 controlling for age, education and gender.
26
27
28
29
30
31
32
33
34
35
36
37
38

39 **Public involvement**

40
41 The research setup (design and outcome measures) was discussed with an advisory
42 board consisting of institutions (e.g., local municipalities) and representatives of the
43 public (e.g., action groups). The present work has been disseminated in a public report.
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

RESULTS

Sample characteristics

There were no significant fluctuations in sample composition over time in terms of gender, education level and damage to own housing (see Table 2). Young respondents were underrepresented. There was attrition during the study. Dropout characteristics revealed no differences between exposed vs. control groups and no association between dropout and health. Analyses showed no indications that attrition influenced any of the effects reported below. Over time, the average age of participants increased, as young people tended to have a higher likelihood of dropout. It is important to note that additional analyses found no significant interaction effect between age and exposure, suggesting that the effects of exposure were age-independent. Because the sample was not entirely representative and attrition relatively high, we carefully checked the potential consequences thereof and found no indications this influenced results.

Regarding levels of exposure, we know, based on existent data about damage per postal code⁶, that the rates of exposure vary substantially within the region: in central areas up to 100% of homes have reported damage at least once. Outside these areas, there is progressively less damage. A substantial part of the province has (nearly) no damage. Average levels of damage are closely associated with ground motion[23]: In postal-code areas where 0% damage was reported until January 2016, there was hardly any exposure to ground motion (total ground motion $PGA_{cum} = .07$ mm/s²). Only 3% of the sample located in this area suspected having damage due to earthquakes. In the areas where up to 20% damage was previously reported, ground

⁶ Provided by the institution handling damage claims, the Centrum voor Veilig Wonen

1
2
3 motion levels were somewhat higher ($PGA_{cum}=0.64 \text{ mm/s}^2$) and more people, 26% of
4 the sample, indicated suspecting they have damage. And in the areas where 20% to
5
6
7
8 100% had reported damage, ground motion was considerably higher, $PGA_{cum}=4.13$
9
10 mm/s^2 and a very high percentage of our sample, 83%, suspected having damage.

11 12 **The impact of exposure to gas extraction on health over time**

13
14 The analyses of conditional growth models on self-rated health, stress-related health
15 problems and mental health showed consistent results across all three indicators. Table
16
17 3 shows the final results for all variables.
18
19

20
21 Important to note is that, after including control variables, there was a significant
22 effect of exposure to physical ground motion (PGA_{cum}) on all three health indicators:
23
24 more ground motion was associated with poorer health. The effect of time was also
25
26 significant: over time, health deteriorated. In the next step, we included damage to
27
28 housing. Importantly, the effect of ground motion was suppressed by the larger effects
29
30 of exposure to multiple damage on all health indicators ($p's<.01$). This means that
31
32 damage better predicts health outcomes than ground motion. Having damage once had
33
34 no significant effect on any of the health indicators. Only participants with multiple
35
36 damages experienced negative health consequences.
37
38

39
40 In step 3, the significant 'multiple damage (vs no damage) X time' interaction reveals
41
42 that exposure to multiple damages is associated with a deterioration of health over time.
43
44 The inclusion of this interaction variable improved model fit.
45
46
47

48
49 To interpret the effects and assess their magnitude, we calculated odds ratios for
50 health measures at every time point, as well as the average impact of exposure over
51
52 time (Table 4). Inhabitants exposed to damage once are only marginally (and not
53
54
55
56
57
58
59
60

1
2
3 significantly) affected compared with a no-damage control group (odds ratios range
4 from 1.10 to 1.20). Those exposed to damage multiple times are more likely to report
5 poor self-rated health (OR = 1.64, with a 95% confidence interval of 1.31;2.04), more
6 stress-related health symptoms (OR = 2.52 [1.89;3.38]) and less good mental health
7 (OR = 1.81 [1.39;2.37]) than those without damage. This indicates that damage has a
8 considerable impact on participants' health⁷.
9
10
11
12
13
14
15

16
17 The table also suggests that differences between groups increase over time.
18
19 Odds ratios for the difference between those with multiple damage and no damage are
20 considerably higher 21 months after first measurement for self-rated health (OR = 2.00),
21 mental health (OR = 2.32) and stress related health symptoms (OR = 3.36). In terms of
22 relative risk, this means that those whose homes have multiple damage at T5 are 1.61
23 times more likely to report poor health, 2.08 times more likely to report negative mental
24 health and 2.86 times more at risk of elevated levels of stress related health symptoms.
25
26
27
28
29
30
31
32

33 We also compared the weighted means of the OR's of control variables known to
34 be related to health (age, gender, level of education), in order to further assess the
35 magnitude of the damage effect (Figure 1): How does the effect of damage compare to
36 other known health indicators (e.g., level of education)? Looking at the OR's, you see
37 that they are comparable to known correlates of health such as level of education.
38
39
40
41
42
43
44
45

46 **DISCUSSION**

47
48
49 Natural and induced seismicity can have negative consequences for local
50 populations due to (acute or accumulated) health threats and irreversible changes to the
51
52
53

54
55 ⁷ We also investigated whether women's health is affected differently by this stressor than men's, but as
56 evidenced in Table S2 in the supplementary materials, this is not the case.
57
58
59

1
2
3 living environment. Yet, so far studies have not assessed the accumulated impact of
4
5 (the consequences of) induced seismicity on (psychosomatic) health *over time*.
6
7 Moreover, most studies lack a non-exposure control group. The present study
8
9 addresses these shortcomings. Our study provides strong indications that exposure to
10
11 negative side-effects of induced seismicity (e.g., damage to people's homes) constitutes
12
13 an increasing health risk over time.
14
15

16
17 To our knowledge, this is the only study of the long-term impact of induced
18
19 seismicity on health. Therefore, we can only compare our results with the long-term
20
21 impacts of very different types of disaster - limiting comparability. For one, the
22
23 Chernobyl nuclear disaster: Study participants lived in a seriously contaminated area
24
25 approximately 50 miles from Chernobyl. 6.5 years post disaster, inhabitants were twice
26
27 as likely to have negative self-rated health (OR:2.25) and psychological distress
28
29 (OR:1.93), compared to a non-exposed control group[30]. Chernobyl clearly constitutes
30
31 a very different type of disaster and health risk (radiation exposure). The Brisbane
32
33 floods were also very different in many respects (e.g., sudden disaster onset; deaths)
34
35 but with some comparable outcomes, such as considerable damage to homes. 6-7
36
37 months post-disaster, those exposed to flooding were twice as likely to report
38
39 psychological distress compared to the non-exposed[31]. It appears that the health
40
41 impact of these very different and in many ways more 'acute' disasters are, in terms of
42
43 effect size, somewhat comparable to the health impact of the more chronic exposure to
44
45 lower-level seismicity caused by gas extraction. One potential reason for the
46
47 comparable effect sizes, is that our study focused not just on the environmental effect
48
49 (e.g., amount of damage in a particular area) but zoomed in on the subgroup who were
50
51
52
53
54
55
56
57
58
59
60

1
2
3 severely affected because they had multiple instances of damage to their own home.
4
5 We further speculate that the man-made nature of the hazard (the fact that earthquakes
6
7 are induced) may also enhance the impact on the population.
8
9

10 The present work also provides first time insights into the development of
11
12 (psychosomatic) health symptoms in response to chronic disaster. In the area of acute
13
14 disaster response, the few studies on longitudinal health impacts reveal that distress
15
16 decreases over time[32,33], implying recovery of victims. Our findings suggest that for
17
18 chronic disasters/hazards, negative effects can accumulate over time, presumably
19
20 because the recurrent threat leads to an accumulation of stress.
21
22

23 **Limitations**

24
25
26 Younger respondents were somewhat underrepresented in our sample and there
27
28 was attrition over time. However, attrition was no different for the exposed and non-
29
30 exposed groups, unrelated to health outcomes, and all further analyses suggest that
31
32 neither attrition nor sample characteristics had any substantial influence on results and
33
34 conclusions drawn above.
35
36

37
38 Another potential limitation with this type of research is the influence of
39
40 confounding variables. Yet the following suggests effect sizes are robust: 1. The
41
42 exposed and control groups were very similar regarding key population and
43
44 geographical characteristics 2. Follow-up analyses revealed no interactions between
45
46 any of the population characteristics and the effects of exposure.
47
48

49 One of the three health measures included, stress-related health symptoms, was
50
51 an adaptation of a previously validated symptoms list (Van de Berg et al., 2005)
52
53 shortened for this specific study. Although the shortened version was not previously
54
55
56
57
58
59
60

1
2
3 validated, it was psychometrically sound. Also, patterns are comparable across health
4
5 measures, two of which are validated.
6

7
8 One of our exposure measures is self-reported damage. It is possible that
9
10 damage is perceived differently depending on people's health status. Importantly,
11
12 physical exposure to ground motion was associated with significant health effects. But
13
14 effects of damage were stronger. This could be because damage is a more precise and
15
16 proximate indicator of how individuals are affected by exposure, but also because of
17
18 recursive effects of (mental) health on perceived damage..
19
20

21
22 An important issue is generalizability: Is the situation in Groningen comparable to
23
24 other areas with induced seismicity (e.g., fracking, wastewater injections)? We can only
25
26 make reasoned inferences. Induced earthquakes are relatively common in energy
27
28 projects which involve injection[34]. A priori, similar health consequences could occur in
29
30 all sites in which populations are affected by induced earthquakes. Moreover, the
31
32 vulnerability of people exposed to seismicity is likely influenced by similar factors:
33
34 negative consequences are man-made and involve safety, health and social risks
35
36 [10,11]. In sum, although more research on the impact of induced seismicity is needed
37
38 [35], we suggest effects are likely to generalize beyond the Groningen case.
39
40
41

42 **Practical implications**

43
44 The consequences of induced seismicity pose challenges to decision-makers.
45
46 Benefits to the public good need to be balanced against the welfare of local populations
47
48 [19]. As projects involving induced seismicity rapidly grow, governments and
49
50 businesses face decisions whether to invest. Our work provides a case study of what
51
52 occurs if seismicity is not kept in check. It can increase awareness of the vulnerability of
53
54
55
56
57
58
59
60

1
2
3 exposed populations and provide important input for future decision making, monitoring
4
5 and contingency planning.
6

7 **Conclusion**

8
9
10 Recent years have seen a rise in induced seismicity. Little is known about the
11
12 (longitudinal) impact thereof on (psychosomatic) health. The present study is the first to
13
14 our knowledge evidencing the long-term impact of induced seismicity on health.
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 **Funding:** This study was funded by the National Coordinator Groningen.
4

5 **Contributorship:** KS, BK, JR, JB, FO, FG and TP contributed to the research
6 questions and study design. JR and FO contributed to data collection. BK and TP
7 conducted statistical analyses. KS, BK and TP interpreted the results and wrote the
8 initial draft of the manuscript. All authors commented on the final draft of the manuscript.
9
10 BK and TP had full access to the data in the study and can take responsibility for the
11 integrity of the data and the accuracy of the data analysis.
12
13

14 **Conflict of Interest:** The authors declare that they have no conflict of interest.
15
16

17 **Ethical approval:** All procedures performed in studies involving human participants
18 were in accordance with the ethical standards of the ethical board of the department of
19 psychology of the University of Groningen, The Netherlands (research code ppo-015-
20 085).
21
22

23 **Informed consent:** Informed consent was obtained from all individual participants
24 included in the study.
25
26

27 **Data sharing statement:** All data collected for this study are not publicly available.
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Table 1.
List of definitions

Conventional gas extraction	Extraction through drilling in deep subsoil reservoirs without the injection of chemical liquids.
Fracking	A well stimulation technique in which a rock is fractured by a pressured liquid.
Induced seismicity	Seismic events that are a result of human activity.
Natural seismicity	Seismic events that have a natural cause (e.g., volcanic eruption).
Peak ground acceleration	Measure of the largest increase in ground motion, recorded by a particular station during an earthquake.
Psychosomatic health	Health outcomes involving both mind and body.
Richter scale	Measure of strength of earthquakes with a logarithmic scale.
Shale gas	A natural gas that is trapped in fine grained sediment in rock.
Unconventional gas extraction	Gas reservoirs that require a special stimulation technique to extract gas (e.g., by injecting large quantities of partly chemical fluids underground).

Table 2

Demographic characteristics of participants participating in separate measurements: total number of participants participating in that measurement, decline of number of participants participating as compared to the number of participants participating at T1, mean age, distribution of level of education, distribution of level of damage, distribution of gender, and amount of participants that completed the three health measures in that measurement. Netherlands 2016-2017

		T1	T2	T3	T4	T5
		Feb '16	June '16	Nov '16	Apr '17	Nov '17
Total N		3943	3162	2638	2357	2156
Attrition (compared to T1)		-	19.8%	33.1%	40.2%	45.3%
Age (mean)		56.54	57.75	57.72	58.92	60.00
Level of education (N)	Low	974 (24.7%)	778 (24.6%)	616 (23.4%)	595 (25.2%)	541 (25.1%)
	Middle	1252 (31.8%)	970 (30.7%)	815 (30.9%)	713 (30.3%)	639 (29.6%)
	High	1536 (39.0%)	1241 (39.2%)	1068 (40.5%)	944 (40.1%)	852 (39.5%)
Gender (N)	Male	1970 (50.0%)	1550 (49.0%)	1306 (49.5%)	1185 (50.3%)	1071 (49.7%)
	Female	1855 (47.0%)	1486 (47.0%)	1231 (46.7%)	1100 (46.7%)	993 (46.1%)
Damage to house (N)	None	1483 (37.7%)	1210 (38.3%)	1027 (38.9%)	913 (38.7%)	849 (39.4%)
	One time	916 (23.2%)	626 (19.8%)	554 (21.0%)	505 (21.4%)	459 (21.3%)
	Multiple	1057 (26.8%)	1055 (33.4%)	940 (35.6%)	778 (33.0%)	739 (34.3%)
Perceived health (N)		3830	-	2540	2212	2065
Stress related health symptoms (N)		3776	-	2533	2212	2051
Mental health (N)		3720	2828	2501	2185	2027

Table 3

Unstandardized regression parameter estimates and standard errors for the association between time, damage, and the interaction between time and damage on perceived health, stress-related health symptoms, and mental health – adjusted for sex, age, level of education and ground motion (cumulative PGA). Netherlands 2016-2017.

	Perceived health	Stress-related health symptoms ¹	Mental health
Sex	-0.04 (0.03)	-5.40*** (0.49)	-2.75*** (0.49)
Age	-0.01*** (0.001)	-0.02 (0.02)	0.07*** (0.02)
Level of education (middle)	0.07* (0.03)	0.61 (0.67)	1.30 (0.67)
Level of education (high)	0.23*** (0.03)	3.02*** (0.63)	3.00*** (0.63)
Cumulative PGA	0.0001 (0.004)	0.03 (0.09)	-0.03 (0.08)
Time	-0.01 (0.01)	-0.25* (0.13)	-0.55*** (0.15)
Damage (one time)	-0.03 (0.04)	-0.46 (0.75)	-0.40 (0.67)
Damage (multiple)	-0.15*** (0.04)	-4.31*** (0.76)	-3.70*** (0.69)
Time * Damage (one time)	-0.01 (0.01)	-0.13 (0.20)	-0.05 (0.24)
Time * Damage (multiple)	-0.03** (0.01)	-0.45* (0.19)	-0.56* (0.23)
Constant	3.88*** (0.03)	80.19*** (0.67)	78.12*** (0.65)
Observations	9,722	9,121	9,180
Log Likelihood	-9,487.06	-36,274.03	-35,912.43
Akaike Inf. Crit.	19,004.11	72,578.06	71,854.87
Bayesian Inf. Crit.	19,111.84	72,684.83	71,961.74

Note. *p<0.05; **p<0.01; ***p<0.001

1. Stress-related health symptoms were reverse-coded such that higher levels indicate less stress

Table 4

Proportion of participants who have poor health and OR of participants who have poor health with damage (compared to those with no damage) across measurements, with 95% confidence intervals – adjusted for age, gender and level of education. Netherlands 2016-2017

Measurement	Damage	Percentage poor health	Odds ratio
Perceived health			
T1	None	22.2% [19.9%;24.5%]	-
	One time	22.5% [19.6%;25.4%]	1.02 [0.82;1.26]
	Multiple	25.6% [22.7%;28.4%]	1.21 [0.99;1.47]
T3	None	21.6% [18.8%;24.3%]	-
	One time	24.4% [20.5%;28.3%]	1.17 [0.90;1.53]
	Multiple	32.4% [29.2%;35.7%]	1.75 [1.41;2.18]
T4	None	21.3% [18.4%;24.2%]	-
	One time	30.0% [25.7%;34.4%]	1.60 [1.22;2.09]
	Multiple	35.5% [31.8%;39.2%]	2.06 [1.63;2.61]
T5	None	23.6% [20.3%;26.9%]	-
	One time	27.5% [22.9%;32.1%]	1.23 [0.92;1.65]
	Multiple	38.0% [34.0%;42.0%]	2.00 [1.57;2.55]
Weighted average	None	22.1% [19.4%;24.9%]	-
	One time	25.6% [21.8%;29.4%]	1.20 [0.93;1.55]
	Multiple	31.8% [28.5%;35.2%]	1.64 [1.31;2.04]
Symptoms			
T1	None	9.2% [7.7%;10.8%]	-
	One time	10.0% [7.9%;12.1%]	1.09 [0.81;1.47]
	Multiple	17.3% [14.9%;19.7%]	2.08 [1.62;2.68]
T3	None	7.1% [5.5%;8.8%]	-
	One time	6.5% [4.3%;8.6%]	0.90 [0.58;1.37]
	Multiple	13.7% [11.4%;16.1%]	2.09 [1.55;2.85]
T4	None	8.1% [6.2%;10.0%]	-
	One time	9.4% [6.7%;12.1%]	1.18 [0.78;1.75]
	Multiple	21.8% [18.7%;25.0%]	3.24 [2.40;4.42]
T5	None	7.1% [5.3%;9.0%]	-
	One time	9.1% [6.3%;11.9%]	1.30 [0.84;1.99]
	Multiple	20.3% [17.0;23.5%]	3.36 [2.45;4.68]
Weighted average	None	8.0% [6.3%;9.8%]	-
	One time	8.8% [6.4%;11.2%]	1.10 [0.75;1.60]
	Multiple	18.0% [15.3%;20.7%]	2.52 [1.89;3.38]
Mental health			
T1	None	8.6% [7.1%;10.2%]	-
	One time	9.0% [7.0%;11.0%]	1.04 [0.77;1.41]
	Multiple	12.4% [10.3%;14.5%]	1.51 [1.16;1.95]
T2	None	8.7% [7.0%;10.3%]	-
	One time	9.2% [6.9%; 11.6%]	1.08 [0.76;1.51]

	Multiple	18.2% [15.6%;20.7%]	2.37 [1.83;3.07]
T3	None	11.1% [9.0%;13.2%]	
	One time	12.0% [9.2%;14.9%]	1.10 [0.79;1.51]
	Multiple	14.5% [12.1%;16.9%]	1.36 [1.04;1.77]
T4	None	11.8% [9.6%;14.1%]	
	One time	11.8% [8.9%;14.7%]	1.00 [0.71;1.39]
	Multiple	20.2% [17.2%;23.3%]	1.90 [1.46;2.47]
T5	None	9.2% [7.1%;11.4%]	
	One time	12.5% [9.3%;15.7%]	1.40 [0.97;2.02]
	Multiple	19.1% [15.9%;22.2%]	2.32 [1.74;3.12]
Weighted average	None	9.7% [7.9%;11.6%]	-
	One time	10.6% [8.1%;14.2%]	1.10 [0.79;1.53]
	Multiple	16.4% [13.8%;19.0%]	1.81 [1.39;2.37]

Note. Scores were categorised as low health as follows: 1) very poor, poor, or fair perceived health; 2) a score below 60 for stress related health symptoms, and 3) a score below 60 for mental health.

REFERENCES

- 1 Konkel L. In the Neighborhood of 18 Million: Estimating How Many People Live Near Oil and Gas Wells. *Environ Health Perspect* 2017;**125**:UNSP 124003.
- 2 U.S. Energy Information Administration. United States Shale gas reserves per state. 2017 Available at: https://www.eia.gov/dnav/ng/ng_enr_shalegas_a_EPG0_R5301_Bcf_a.htm. Accessed 29/01/, 2019.
- 3 Dai W, Chen L, Lai Z, et al. The incidence of post-traumatic stress disorder among survivors after earthquakes: A systematic review and meta-analysis. *BMC Psychiatry* 2016;**16**.
- 4 Neria Y, Nandi A, Galea S. Post-traumatic stress disorder following disasters: A systematic review. *Psychol Med* 2008;**38**:467-480.
- 5 Galea S, Nandi A, Vlahov D. The epidemiology of post-traumatic stress disorder after disasters. *Epidemiol Rev* 2005;**27**:78-91.
- 6 Norris FH, Friedman MJ, Watson PJ. 60,000 disaster victims speak: Part II. Summary and implications of the disaster mental health research. *Psychiatry: Interpersonal and biological processes* 2002;**65**:240-260.
- 7 Rubonis AV, Bickman L. Psychological impairment in the wake of disaster: The disaster- psychopathology relationship. *Psychol Bull* 1991;**109**:384.
- 8 Keranen KM, Weingarten M. Induced Seismicity. *Annual Review of Earth and Planetary Sciences, Vol 46* 2018;**46**:149-174.
- 9 van der Elst, Nicholas J., Page MT, Weiser DA, et al. Induced earthquake magnitudes are as large as (statistically) expected. *Journal of Geophysical Research-Solid Earth* 2016;**121**:4575-4590.
- 10 Couch SR, Kroll-Smith JS. The chronic technical disaster: Toward a social scientific perspective. *Social Science Quarterly* 1985;**66**:564.
- 11 Sangaramoorthy T, Jamison AM, Boyle MD, et al. Place-based perceptions of the impacts of

1
2
3 fracking along the Marcellus Shale. *Soc Sci Med* 2016;**151**:27-37.

4
5 12 Rabinowitz PM, Slizovskiy IB, Lamers V, et al. Proximity to Natural Gas Wells and Reported
6
7 Health Status: Results of a Household Survey in Washington County, Pennsylvania. *Environ*
8
9 *Health Perspect* 2015;**123**:21-26.

10
11 13 Steinzor N, Subra W, Sumi L. Investigating links between shale gas development and health
12
13 impacts through a community survey project in Pennsylvania. *New solutions : a journal of*
14
15 *environmental and occupational health policy : NS* 2013;**23**:55-83.

16
17 14 Tustin AW, Hirsch AG, Rasmussen SG, et al. Associations between Unconventional Natural
18
19 Gas Development and Nasal and Sinus, Migraine Headache, and Fatigue Symptoms in
20
21 Pennsylvania. *Environ Health Perspect* 2017;**125**:189-197.

22
23 15 Weinberger B, Greiner LH, Walleigh L, et al. Health symptoms in residents living near shale
24
25 gas activity: A retrospective record review from the Environmental Health Project. *Preventive*
26
27 *medicine reports* 2017;**8**:112-115.

28
29 16 Wilson MP, Foulger GR, Gluyas JG, et al. HiQuake: The human-induced earthquake
30
31 database. *Seismol Res Lett* 2017;**88**:1560-1565.

32
33 17 Aczel MR, Makuch KE. Shale, Quakes, and High Stakes: Regulating Fracking-Induced
34
35 Seismicity in Oklahoma, USA and Lancashire, UK. *Case Studies in the Environment* 2019;.

36
37 18 Keranen KM, Weingarten M, Abers GA, et al. Sharp increase in central Oklahoma seismicity
38
39 since 2008 induced by massive wastewater injection. *Science* 2014;**345**:448-451.

40
41 19 Fleming RC, Reins L. Shale gas extraction, precaution and prevention: A conversation on
42
43 regulatory responses. *Energy Research & Social Science* 2016;**20**:131-141.

44
45 20 Dutch Safety Board. Earthquake risks in Groningen. Research concerning the role
46
47 population safety played in decision making procedures about gas extraction (1959-2014) .
48
49 2015;.

50
51 21 Postmes, T., Stroebe, K., Richardson, J., LeKander, B., Oldersma, F., Broer, J. & Greven, F.
52
53 Consequences of ground motion for the Groningen population: Experienced safety, health and
54
55
56
57
58

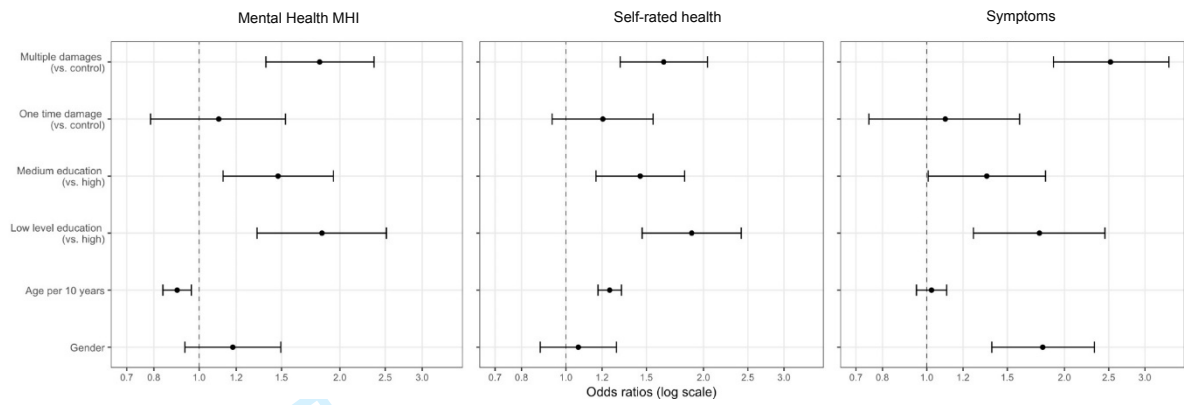
- 1
2
3 future perspective 2016-2017. *University of Groningen* 2018;.
- 4
5 22 Vlek C. Rise and reduction of induced earthquakes in the Groningen gas field, 1991-2018:
6 statistical trends, social impacts, and policy change. *Environ Earth Sci* 2019;**78**:59.
- 7
8
9 23 Geurts C, Steenbergen R. Note for the Dutch State Supervision of Mines: The relation
10 between Peak Ground Acceleration and the risk of damage for induced earthquakes in
11 Groningen. *The Netherlands Organisation for Applied Scientific Research* 2016;.
- 12
13
14 24 Pappas G. Health interview surveys: Towards international harmonization of methods and
15 instruments - deBruin,A, Picavet,HSJ, Nossikoy,A. *Soc Sci Med* 1997;**44**:1431-1432.
- 16
17
18 25 Ware JE, Gandek B, IQOLA Project. Overview of the SF-36 Health Survey and the
19 International Quality of Life Assessment (IQOLA) Project. *J Clin Epidemiol* 1998;**51**:903-912.
- 20
21
22 26 Van den Berg B, Yzermans CJ, Van der Velden, Peter G., et al. Risk Factors for
23 Unexplained Symptoms After a Disaster: A Five-Year Longitudinal Study in General Practice.
24
25
26
27
28
29
30
31 27 Berwick DM, Murphy JM, Goldman PA, et al. Performance of a five-item mental health
32 screening test. *Med Care* 1991;.
- 33
34
35 28 Raudenbush SW, Bryk AS. Hierarchical linear models: Applications and data analysis
36 methods. : Sage 2002.
- 37
38
39 29 Rumpf H, Meyer C, Hapke U, et al. Screening for mental health: validity of the MHI-5 using
40 DSM-IV Axis I psychiatric disorders as gold standard. *Psychiatry Res* 2001;**105**:243-253.
- 41
42
43 30 Havenaar J, Rumyantzeva G, Kasyanenko A, et al. Health effects of the Chernobyl disaster:
44 Illness or illness behavior? A comparative general health survey in two former Soviet regions.
45
46
47
48
49
50 31 Alderman K, Turner LR, Tong S. Assessment of the Health Impacts of the 2011 Summer
51 Floods in Brisbane. *Dis Med Public Health Prep* 2013;**7**:380-386.
- 52
53
54 32 Lowell A, Suarez-Jimenez B, Helpman L, et al. 9/11-related PTSD among highly exposed
55 populations: a systematic review 15 years after the attack. *Psychol Med* 2018;**48**:537-553.
- 56
57
58
59
60

1
2
3 33 van der Velden, Peter G., Wong A, Boshuizen HC, et al. Persistent mental health
4 disturbances during the 10years after a disaster: Four-wave longitudinal comparative study.
5
6
7 *Psychiatry Clin Neurosci* 2013;**67**:110-118.

8
9 34 Ellsworth WL. Injection-induced earthquakes. *Science* 2013;**341**:1225942.

10
11 35 Hirsch JK, Smalley KB, Selby-Nelson EM, et al. Psychosocial Impact of Fracking: a Review
12 of the Literature on the Mental Health Consequences of Hydraulic Fracturing. *International*
13
14
15
16 *Journal of Mental Health and Addiction* 2018;**16**:1-15.

Figure 1. Weighted average odds ratios.



For peer review only

Supplementary materials

Table S1

Demographic characteristics of participants completing separate measurements per level of damage: total sample size, mean age, distribution of level of education, distribution of level of damage, distribution of gender, and amount of participants that completed the health measures. Netherlands 2016-2017

Damage to house at T1		T1 Feb '16	T2 June '16	T3 Nov '16	T4 Apr '17	T5 Nov '17	
None	Total N	1483	1172	968	889	804	
	Age (mean)	57.66	59.11	59.13	60.28	61.48	
	Level of education (N)	Low	433 (29.2%)	343 (29.3%)	266 (27.5%)	270 (30.4%)	241 (30.0%)
		Middle	460 (31.0%)	351 (29.9%)	290 (30.0%)	255 (26.7%)	226 (28.1%)
		High	565 (38.1%)	456 (38.9%)	396 (40.9%)	349 (39.3%)	324 (40.3%)
	Gender (N)	Male	794 (53.5%)	621 (53.0%)	515 (53.2%)	471 (53.0%)	427 (53.1%)
		Female	689 (46.5%)	551 (47.0%)	453 (46.8%)	418 (47.0%)	377 (46.9%)
	Perceived health (N)	1473	-	934	838	787	
	Stress related health symptoms (N)	1458	-	937	839	783	
	Mental health (N)	1438	1054	920	831	772	
One time	Total N	916	733	608	562	493	
	Age (mean)	58.36	58.92	58.81	60.11	60.91	
	Level of education (N)	Low	240 (26.2%)	194 (26.5%)	155 (25.5%)	146 (26.0%)	134 (27.2%)
		Middle	295 (32.2%)	235 (32.1%)	195 (32.1%)	182 (32.4%)	159 (32.3%)
		High	363 (39.6%)	295 (40.2%)	250 (41.1%)	227 (40.4%)	193 (39.1%)
	Gender (N)	Male	508 (55.5%)	401 (54.7%)	345 (56.7%)	326 (58.0%)	282 (57.2%)
		Female	407 (44.4%)	332 (45.3%)	263 (43.3%)	236 (42.0%)	211 (42.8%)
	Perceived health (N)	910	-	587	524	467	
	Stress related health symptoms (N)	897	-	584	525	466	
	Mental health (N)	898	669	581	520	459	
Multiple	Total N	1057	825	704	609	558	
	Age (M)	54.06	55.57	55.60	56.71	57.70	
	Level of education (N)	Low	215 (20.3%)	168 (20.4%)	133 (18.9%)	120 (19.7%)	110 (19.7%)
		Middle	381 (36.0%)	289 (35.0%)	246 (34.9%)	213 (35.0%)	188 (33.8%)
		High	445 (42.1%)	356 (43.1%)	315 (44.7%)	268 (44.0%)	253 (45.4%)
	Gender (N)	Male	493 (46.6%)	385 (46.6%)	323 (45.9%)	284 (46.7%)	269 (48.3%)

	Female	563	440	381	325	289
		(53.3%)	(53.3%)	(54.1%)	(53.4%)	(51.9%)
Perceived health (N)		1048	-	683	578	537
Stress related health symptoms (N)		1041	-	675	577	530
Mental health (N)		1018	739	674	570	528

For peer review only

Table S2

Unstandardized regression parameter estimates and standard errors for the association between time, damage, and the interaction between time and damage on perceived health, stress-related health symptoms, and mental health, and the interaction between gender and damage on perceived health, stress-related health symptoms, and mental health – adjusted for sex, age, level of education and ground motion (cumulative PGA). Netherlands 2016-2017.

	Perceived health	Stress-related health symptoms ¹	Mental health
Sex	-0.06 (0.04)	-5.30*** (0.79)	-2.97*** (0.75)
Age	-0.01*** (0.001)	-0.02 (0.02)	0.06*** (0.02)
Level of education (middle)	0.07* (0.03)	0.79 (0.71)	1.28 (0.67)
Level of education (high)	0.23*** (0.03)	3.08*** (0.66)	2.97*** (0.63)
Cumulative PGA	0.0001 (0.004)	0.003 (0.09)	-0.03 (0.08)
Time	-0.01 (0.01)	-0.30* (0.13)	-0.55*** (0.15)
Damage (one time)	-0.04 (0.05)	-0.35 (0.99)	-0.34 (0.86)
Damage (multiple)	-0.17*** (0.05)	-4.57*** (1.02)	-4.14*** (0.90)
Time * Damage (one time)	-0.01 (0.01)	-0.12 (0.21)	-0.05 (0.24)
Time * Damage (multiple)	-0.03** (0.01)	-0.38 (0.20)	-0.56* (0.23)
Gender * Damage (one time)	0.02 (0.06)	-0.19 (1.27)	-0.16 (1.19)
Gender * Damage (multiple)	0.03 (0.06)	-0.23 (1.22)	0.86 (1.15)
Constant	3.88*** (0.04)	80.39*** (0.78)	78.25*** (0.71)
Observations	9,722	8,588	9,180
Log Likelihood	-9,486.91	-33,969.29	-35,912.03
Akaike Inf. Crit.	19,007.82	67,972.57	71,858.07
Bayesian Inf. Crit.	19,129.92	68,092.56	71,979.19

Note. *p<0.05; **p<0.01; ***p<0.001

1. Stress-related health symptoms were reverse-coded such that higher levels indicate less stress

STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No.	Recommendation	Page No.	Relevant text from manuscript
Title and abstract	1	(a) Indicate the study’s design with a commonly used term in the title or the abstract	1/2	Title is mentioned on page 1
		(b) Provide in the abstract an informative and balanced summary of what was done and what was found	2	
Introduction				
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	4/5	
Objectives	3	State specific objectives, including any prespecified hypotheses	5	“The present work was designed to address the lack of information regarding the long-term impact of induced seismicity for residents: It studies the longitudinal (psychosomatic) health impact of induced seismicity on a group exposed to the consequences of seismicity (damage to housing) versus a control group not exposed to these consequences. The present study is novel in charting the chronic impact of exposure to damage on health over a time period of almost two years, on a large sample. We tested the following hypotheses: 1. Exposure versus non-exposure will have a negative impact on (psychosomatic) health outcomes. 2. Increases in

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

				exposure are related to poorer health outcomes.
Methods				
Study design	4	Present key elements of study design early in the paper	6-9	
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	7	. Participants (t1: N=3934; t5: N=2156) completed measures at 5 time points during 2 years (T1: February 2016, T2: June 2016; T3: October 2016; T4: April 2017; T5: October 2017; see Table 2
Participants	6	<p>(a) <i>Cohort study</i>—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up</p> <p><i>Case-control study</i>—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls</p> <p><i>Cross-sectional study</i>—Give the eligibility criteria, and the sources and methods of selection of participants</p> <p>(b) <i>Cohort study</i>—For matched studies, give matching criteria and number of exposed and unexposed</p> <p><i>Case-control study</i>—For matched studies, give matching criteria and the number of controls per case</p>	7	
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	7-9	
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	7-9	
Bias	9	Describe any efforts to address potential sources of bias	9	
Study size	10	Explain how the study size was arrived at	6-7	

Continued on next page

1					
2	Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	9-10	
3					
4	Statistical methods	12	(a) Describe all statistical methods, including those used to control for confounding	9-10	
5			(b) Describe any methods used to examine subgroups and interactions	9-10	
6			(c) Explain how missing data were addressed	9	Participants with missing data on the health indices were retained, as multilevel modelling is robust to missingness in estimation of model outcomes. See Table 2 for an overview of the number of participants completing each health measure per time point.
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19			(d) Cohort study—If applicable, explain how loss to follow-up was addressed	11	we conducted analyses to test whether loss to follow up affected the nature of the results. As we outline on page 11, this was not the case.
20			Case-control study—If applicable, explain how matching of cases and controls was addressed		
21			Cross-sectional study—If applicable, describe analytical methods taking account of sampling strategy		
22					
23					
24					
25			(e) Describe any sensitivity analyses		
26					
27	Results				
28	Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	20	Table 2
29			(b) Give reasons for non-participation at each stage	N/A	
30			(c) Consider use of a flow diagram	N/A	
31					
32					
33	Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	20	Table 2
34			(b) Indicate number of participants with missing data for each variable of interest	N/A	
35			(c) Cohort study—Summarise follow-up time (eg, average and total amount)		
36					
37					
38	Outcome data	15*	Cohort study—Report numbers of outcome events or summary measures over time		
39			Case-control study—Report numbers in each exposure category, or summary measures of exposure		
40			Cross-sectional study—Report numbers of outcome events or summary measures		
41					
42					

1				
2	Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	12-13 &21/22
3				Table 3/4
4				
5				
6			(b) Report category boundaries when continuous variables were categorized	12-13& 21/11
7				Tables 3/4
8				
9			(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	
10				

Continued on next page

For peer review only

Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	
Discussion			
Key results	18	Summarise key results with reference to study objectives	10-11
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	12-13
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	10-13
Generalisability	21	Discuss the generalisability (external validity) of the study results	12-13
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	24

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at <http://www.plosmedicine.org/>, Annals of Internal Medicine at <http://www.annals.org/>, and Epidemiology at <http://www.epidem.com/>). Information on the STROBE Initiative is available at www.strobe-statement.org.

BMJ Open

Chronic disaster impact: the long-term psychological and physical health consequences of housing damage due to induced earthquakes

Journal:	<i>BMJ Open</i>
Manuscript ID	bmjopen-2020-040710.R1
Article Type:	Original research
Date Submitted by the Author:	04-Jan-2021
Complete List of Authors:	Stroebe, Katherine; Rijksuniversiteit Groningen, Social Psychology Kanis, Babet; Rijksuniversiteit Groningen, Social Psychology Richardson, Justin; Rijksuniversiteit Groningen, Social Psychology Oldersma, Frans; Department for Statistics and Research, Municipality of Groningen, Groningen, Netherlands Broer, Jan; Municipal Health Services Groningen, ABPG; Greven, Frans; Municipal Health Services Groningen, the Netherlands, Department of Environmental Health Postmes, Tom; Rijksuniversiteit Groningen, Social Psychology
Primary Subject Heading:	Public health
Secondary Subject Heading:	Mental health, Public health
Keywords:	MENTAL HEALTH, EPIDEMIOLOGY, PUBLIC HEALTH

SCHOLARONE™
Manuscripts



I, the Submitting Author has the right to grant and does grant on behalf of all authors of the Work (as defined in the below author licence), an exclusive licence and/or a non-exclusive licence for contributions from authors who are: i) UK Crown employees; ii) where BMJ has agreed a CC-BY licence shall apply, and/or iii) in accordance with the terms applicable for US Federal Government officers or employees acting as part of their official duties; on a worldwide, perpetual, irrevocable, royalty-free basis to BMJ Publishing Group Ltd ("BMJ") its licensees and where the relevant Journal is co-owned by BMJ to the co-owners of the Journal, to publish the Work in this journal and any other BMJ products and to exploit all rights, as set out in our [licence](#).

The Submitting Author accepts and understands that any supply made under these terms is made by BMJ to the Submitting Author unless you are acting as an employee on behalf of your employer or a postgraduate student of an affiliated institution which is paying any applicable article publishing charge ("APC") for Open Access articles. Where the Submitting Author wishes to make the Work available on an Open Access basis (and intends to pay the relevant APC), the terms of reuse of such Open Access shall be governed by a Creative Commons licence – details of these licences and which [Creative Commons](#) licence will apply to this Work are set out in our licence referred to above.

Other than as permitted in any relevant BMJ Author's Self Archiving Policies, I confirm this Work has not been accepted for publication elsewhere, is not being considered for publication elsewhere and does not duplicate material already published. I confirm all authors consent to publication of this Work and authorise the granting of this licence.

1
2
3
4
5
6 Chronic disaster impact: the long-term psychological and physical health consequences
7 of housing damage due to induced earthquakes
8

9 Stroebe, K.¹, Kanis, B.¹, Richardson, J.¹, Oldersma, F.², Broer, J.³, Greven, F.³ & Postmes, T.¹,
10
11

12
13 1. University of Groningen, Faculty of Behavioral and Social Sciences, Groningen,
14 Netherlands

15 2. Department for Statistics and Research, Municipality of Groningen, Groningen,
16 Netherlands

17 3. Municipal Health Services Groningen, Groningen, Netherlands
18
19

20 Corresponding author: Katherine Stroebe, k.e.stroebe@rug.nl, +313636509
21
22

Abstract

Objectives: To evaluate the long-term (psychosomatic) health consequences of man-made earthquakes compared to a non-exposure control group. Exposure was hypothesized to have an increasingly negative impact on health outcomes over time.

Setting — Large scale gas extraction in the Netherlands causing earthquakes and considerable damage.

Participants — A representative sample of inhabitants randomly selected from municipal population records; contacted 5 times during 21 months (T1:N=3934; T5:N=2150; mean age: 56.54; 50%males; At T5, N=846 (39.3%) had no, 459 (21.3%) once, and 736 (34.2%) repeated damages.

Main measures — (Psychosomatic) health outcomes: Self rated health and Mental Health Inventory (both: validated; Short Form Health Survey); stress related health symptoms (shortened version of previously validated symptoms list) Independent variable: Exposure to the consequences of earthquakes assessed via physical (Peak Ground Acceleration, PGA) and personal exposure (damage to housing: none, once, repeated).

Results: Exposure to induced earthquakes has negative health consequences mainly for those whose homes were damaged repeatedly. Compared to a no-damage control group, repeated damage was associated with lower self-rated health (OR:1.64), mental health (OR:1.83) and more stress-related health symptoms (OR:2.52). Effects increased over time: In terms of relative risk, by T5, those whose homes had repeated damage were respectively 1.60 and 2.11 times more likely to report poor health and negative mental health and 2.84 times more at risk of elevated stress related health symptoms. Results for physical exposure were comparable.

Conclusion

This is the first study to provide evidence that induced earthquakes can have negative health consequences for inhabitants over time. It identifies the subpopulation particularly at risk: people with repeated damages/high PGA). Findings can have important implications for the prevention of negative health consequences of induced earthquakes.

1
2
3 Keywords: induced earthquakes; seismicity; longitudinal; psychosomatic health, gas extraction
4
5

6
7 **Strengths and limitations**

- 8 ● The present study employs a longitudinal panel design with 5 measurement
9 points to study health consequences of gas extraction
10
11 ● The study has an exposed (residents with damage to housing) and a non-
12 exposed (residents with no damage) control group
13
14 ● Two health measures (self-rated health; Mental Health Inventory) were
15 previously validated, the third was an adaptation of a previously validated
16 symptoms list
17
18 ● Younger respondents were somewhat underrepresented in our sample
19
20 ● There was 45.3% attrition over time but attrition was no different for the exposed
21 versus non-exposed groups and was unrelated to health outcomes.
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

INTRODUCTION

Recent years have seen a rise in induced seismicity due to human activities such as fracking, mining or gas extraction. This development is expected to continue. While smaller in magnitude than natural seismicity, induced seismicity can expose populations to considerable physical (e.g., damage to housing) and social risks (e.g., conflicts between residents and institutions). Moreover, this exposure is recurrent and chronic over time. While there is some insight into the long-term health risks of naturally occurring seismicity, little is known about the impact of induced seismicity. Given the increased use of energy technologies associated with seismicity, also in densely populated areas, knowledge of its health impact is important [1, 2] (see also Table 1 for definitions of gas-extraction related terminology).

Naturally occurring seismicity is associated with mental health problems in survivors (e.g., depression, PTSD)[3-5]. While there has been some increase in studies considering longitudinal health effects of seismicity, lack of longitudinal design and an unexposed control group have been highlighted as major concerns for studies of natural disasters [3, 5, 6]. Moreover, the impact of natural- cannot be equated with that of induced- seismicity for several reasons: Systematic reviews suggest there is *lower* prevalence of mental health impairment for natural compared to human/technological disasters [7, 8]; but see [9]. Additionally, different stressors are at play: Natural seismicity can be of greater magnitude, causing death and extensive damages to buildings. For induced seismicity, the maximum magnitude of earthquakes tends to be smaller [10, 11]. Risks involve damage to property and an incremental impact on health,

1
2
3 as residents are exposed to long-term stressors (e.g., damages; changing community
4 relations; conflicts of interest with powerful institutions [12, 13]).
5
6

7
8 Factual information regarding the health impact of induced seismicity is sparse.
9
10 Cross-sectional self-report studies [14-16] and an evaluation of health records of
11 exposed adults[17] in the context of unconventional gas extraction, suggest
12 associations between induced seismicity and increased (psychosomatic) health
13 symptoms (e.g., sleep disruption, headaches, stress). It is difficult to draw conclusions
14 regarding the impact of seismicity from such studies: Exposure to (the consequences
15 of) seismicity is not distinguished from other risk factors (e.g., wastewater injections).
16 Additionally, most studies lack a non-exposed control group and thus a reliable baseline
17 comparison. None we are aware of consider the longitudinal effects of exposure.
18
19
20
21
22
23
24
25
26
27

28 This lack of information regarding the (long-term) impact of induced seismicity on
29 health is problematic. The occurrence of induced earthquakes is increasingly common
30 across the globe, 1174 projects worldwide report induced seismicity [18]. High-profile
31 cases of induced earthquakes have occurred in Oklahoma, U.S.A., and (on a smaller
32 scale) Lancashire, UK [19, 20]. There are rising concerns regarding the consequences
33 thereof within exposed populations, coupled with calls to policy makers for monitoring
34 and contingency planning [19]. Policy makers need to weigh the wider economic (and
35 sometimes environmental) benefits against potential drawbacks for exposed residents
36 [21].
37
38
39
40
41
42
43
44
45
46
47
48

49 The present work was designed to address the lack of information regarding the
50 long-term impact of induced seismicity for residents: It studies the longitudinal
51 (psychosomatic) health impact of induced seismicity on a group exposed to the
52
53
54
55
56
57
58
59
60

1
2
3 consequences of seismicity (damage to housing) versus a control group not exposed to
4 these consequences. The study was conducted in the province of Groningen,
5
6 Netherlands, where conventional gas extraction from the largest gas field in Europe
7
8 takes place¹. While the magnitude of seismic events (up to 3.6 Richter) is generally
9
10 considered 'light', their magnitude has increased over the past 30 years, making this a
11
12 chronic disaster, and their impact is felt well beyond the gas field boundaries. The
13
14 earthquakes cause considerable damage to housing in a region not prepared for
15
16 seismic activity [22] and governmental responses to damage compensation have been
17
18 considered inadequate [23].

19
20
21
22
23
24 The present study is novel in charting the chronic impact of exposure to damage
25
26 on health over a time period of almost two years, on a large sample. We tested the
27
28 following hypotheses: 1. Exposure versus non-exposure will have a negative impact on
29
30 (psychosomatic) health outcomes. 2. Increases in exposure are related to poorer health
31
32 outcomes.

33 34 35 36 37 **METHOD**

38 39 40 41 **Setting and exposure**

42
43 The study was conducted in the province of Groningen, Netherlands, where
44
45 conventional gas extraction from the largest gas field in Europe takes place. Exposed
46
47 residents experience rising concerns about physical safety, loss of property value and
48
49 uncertainty about the future[23, 24].The benefits of extraction flow to the operator (the
50
51
52
53
54

55
56 ¹ See Figure S1 for more information on seismicity in this province
57
58
59
60

1
2
3 Netherlands' petroleum company) and the national government, while damage repair
4 and compensation by these entities has been criticized as being inadequate[23].
5
6
7

8 Seismicity has increased over time. While the magnitude of seismic events (up to
9 3.6 Richter) is generally considered 'light', their impact is felt well beyond the gas field
10 boundaries. Also, multiple factors (limited depth & high rates of occurrence of
11 earthquakes; surface constitution) contribute to considerable damage to housing in a
12 region not prepared for seismic activity[22]. For these reasons, documented damage
13 has proven the most proximal measure of exposure, compared to indicators of
14 seismicity[25].
15
16
17
18
19
20
21
22
23
24
25

26 Sample and recruitment

27
28
29 A stratified random sample was drawn of 25000 residents of the province of Groningen,
30 aged 16 and over, from the official municipal population records which is a complete
31 register of all legal residents. Sampling occurred in areas where damage is reported
32 and from outlying areas where this is not the case. Postal-code areas that were rural
33 and strongly affected by damage were oversampled². Residents received letters with
34 personal login codes and one reminder. Eighteen percent (N=4577) signed up for the
35 study, and later received invitations to all questionnaires. Of these 4577, 86% (3934)
36 filled out the first questionnaire. Baseline equivalence of non-exposed and exposed
37 groups was assessed. Differences between groups were significant but small. Those
38 with multiple damage to homes were slightly younger ($r^2 = .014$), more highly educated
39
40
41
42
43
44
45
46
47
48
49
50
51
52

53
54 _____
55 ² In the Netherlands, 4-number postal-code areas provide reasonably accurate geographic positioning,
56 whilst preserving anonymity. Data about damage in each area was provided by the institution handling
57 damage claims, the Centrum voor Veilig Wonen.
58
59
60

1
2
3 (Cramer's $V=.062$), and more likely to be male ($V=.072$). The first two characteristics
4
5 suggest the exposed group might be slightly healthier. We statistically controlled for
6
7 these characteristics.
8
9

10 11 Data sources

12 13 14 15 16 Procedure

17
18
19 Questionnaires were sent via an email link or by post. A reminder was sent after 2
20
21 weeks. Participants (T1: $N=3934$; T5: $N=2150$) completed measures at 5 time points
22
23 during 2 years (T1: February 2016, T2: June 2016; T3: November 2016; T4: April 2017;
24
25 T5: November 2017; see Table 2).
26
27
28
29

30 31 Study Variables

32
33 *Exposure to consequences of gas extraction* was operationalized in two ways. Physical
34
35 exposure to ground motion was assessed by calculating the cumulative peak ground
36
37 acceleration (PGA_{cum}) on the basis of "shakemaps" provided by the Dutch geological
38
39 survey (KNMI)³. Personal exposure to damage due to gas extraction was assessed
40
41 every timepoint by asking participants to indicate how often their home had been
42
43 damaged (never, once or multiple times)⁴.
44
45
46
47
48
49
50
51
52

53
54 ³ KNMI calculates shakemaps based on motion sensor readings. For each participant, the PGA of all
55 events modelled by KNMI between 2012 and 2017 was summed, to create an index of exposure to
ground motion before and during the study.

56
57 ⁴ See supplementary materials (table S1) for demographic characteristics by level of damage exposure.
58
59

1
2
3 *Demographic variables* included gender, age and completed education level
4
5 (categorized into ‘low’ (no, elementary, or pre-vocational education), ‘middle’ (secondary
6
7 or vocational education), or ‘high’ (higher education) level of education).
8
9

10 *(Psychosomatic) health outcomes* were assessed at (almost) all time points
11
12 (Table 2) as follows via:
13

14 1. The WHO and Statistics Netherlands recommended validated health survey
15
16 item assessing *self-rated health* [26] (‘how good is your health in general?’, from ‘very
17
18 poor’ to ‘excellent’ on a 5 point scale), which is part of the SF-36 [27].
19
20

21 2. *Stress-related health symptoms* were based on a validated scale of symptoms
22
23 of disaster impact [28]. This list of symptoms was shortened by authors (JB, FG, TP):
24
25 symptoms associated with chronic stress were retained⁵. Consequences of exposure to
26
27 toxic substances and noise (e.g., hearing problems) were deemed irrelevant for
28
29 earthquakes and removed. Ten symptoms (stomach problems, heart palpitations,
30
31 headaches, dizziness/lightheadedness, sensitivity to light/sounds, muscle/joint pains,
32
33 irritability, memory/concentration problems, insomnia, tiredness) were assessed by
34
35 asking ‘how often have you experienced the following complaint(s) in the past four
36
37 weeks’ with response options ‘never, rarely, occasionally, often, most times,
38
39 continuously’. Aggregate health index scores were computed for stress-related health
40
41 symptoms, so that individuals have a score of 0 to 100, with 100 representing optimal
42
43 health. Psychometric properties of the aggregate scale were adequate. Correlations
44
45 among items ranged from ordinal rho 0.26 to 0.72 (median=0.39). A single factor
46
47 explained 46% of variance. Scale reliability was good with omega=.90.
48
49
50
51
52

53
54
55 _____
56 ⁵ Notably, at the level of individuals who suffer these complaints they are referred to as “medically
57
58 unexplained” because they can have multiple sources, among which is chronic stress.
59

1
2
3 3. The five-item validated Mental Health Inventory (MHI-5), part of the Short
4 Form Health Survey (SF-36), measuring general *mental health* [27, 29]. The MHI-5 has
5 a score of 0 to 100. A score of 100 represents optimal mental health.
6
7
8
9

10 11 12 Data management and Analysis 13

14
15 Analyses controlled for age, gender and education level. Analyses were weighted
16 to correct for sampling effects of age, gender and degree of exposure of postal-code
17 areas⁶. The weights were developed to counteract any potential distortive effect due to
18 age composition, among others (e.g., because younger people were underrepresented,
19 see results section). We report the weighted results. The unweighted results were very
20 similar.
21
22
23
24
25
26
27

28
29 To assess the impact of exposure to gas extraction on health over time, we
30 constructed multilevel conditional growth models on the three health indices with
31 damage to housing as the (between group) predictor[30]. Participants with missing data
32 on the health indices were retained, as multilevel modelling is robust to missingness in
33 estimation of model outcomes.
34
35
36
37
38
39

40 Models were tested in a step-wise approach, first including control variables
41 (gender, age, level of education) and time. At the next step, physical exposure (PGA_{cum})
42 was added, followed by earthquake damage at time 1 and the increase of damage since
43 time 1. The final model included the interaction between damage and time. Model fit
44
45
46
47
48
49
50
51
52
53

54
55 ⁶ As mentioned, we oversampled rural areas as well as the most heavily exposed areas. The
56 geographical weighting was added to control for this overrepresentation.
57
58
59

1
2
3 was compared to assess which variables best predicted health outcomes. The best
4 fitting models were those including the interaction of damage by time (see Table 3).
5
6

7
8 To highlight the implications of the findings, we distinguished poor and good
9 health on the basis of health scores, enabling us to compute odds ratios (OR) and
10 relative risk. For mental health we used the conventional criterion of MHI < 60 as
11 cutoff[31]. For perceived health we classified “good” and “outstanding” as good health
12 and all other scale points as poor (conform international convention). For symptoms we
13 devised our own cutoff based on distributional characteristics combined with content
14 criteria: A classification of < 60 as poor health resulted in 9% of the unaffected
15 population being classified as such. Odds ratios were calculated in weighted models,
16 controlling for age, education and gender.
17
18
19
20
21
22
23
24
25
26
27
28
29

30 **Public involvement**

31
32 The research setup (design and outcome measures) was discussed with an advisory
33 board consisting of institutions (e.g., local municipalities) and representatives of the
34 public (e.g., action groups). The present work has been disseminated in a public report.
35
36
37
38
39
40

41 **RESULTS**

42 **Sample characteristics**

43
44 There were no significant fluctuations in sample composition over time in terms
45 of gender, education level and damage to own housing (see Table 2). Young
46 respondents were underrepresented. There was attrition during the study. Dropout
47 characteristics revealed no differences between exposed vs. control groups and no
48 association between dropout and health. Analyses showed no indications that attrition
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 influenced any of the effects reported below. Over time, the average age of participants
4 increased, as young people tended to have a higher likelihood of dropout. It is important
5 to note that additional analyses found no significant interaction effect between age and
6 exposure, suggesting that the effects of exposure were age-independent. Because the
7 sample was not entirely representative and attrition relatively high, we carefully checked
8 the potential consequences thereof and found no indications this influenced results.
9

10
11
12
13
14
15
16
17 Regarding levels of exposure, we know, based on existent data about damage
18 per postal code⁷, that the rates of exposure vary substantially within the region: in
19 central areas up to 100% of homes have reported damage at least once. Outside these
20 areas, there is progressively less damage. A substantial part of the province has
21 (nearly) no damage. Average levels of damage are closely associated with ground
22 motion[25]: In postal-code areas where 0% damage was reported until January 2016,
23 there was hardly any exposure to ground motion (total ground motion $PGA_{cum}=0.07$
24 mm/s^2). Only 3% of the sample located in this area suspected having damage due to
25 earthquakes. In the areas where up to 20% damage was previously reported, ground
26 motion levels were somewhat higher ($PGA_{cum}=0.64 mm/s^2$) and more people, 26% of
27 the sample, indicated suspecting they have damage. And in the areas where 20% to
28 100% had reported damage, ground motion was considerably higher, $PGA_{cum}=4.13$
29 mm/s^2 and a very high percentage of our sample, 83%, suspected having damage.
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

47 **The impact of exposure to gas extraction on health over time**

48
49
50
51
52
53
54

55
56 ⁷ Provided by the institution handling damage claims, the Centrum voor Veilig Wonen
57
58
59
60

1
2
3 The analyses of conditional growth models on self-rated health, stress-related health
4 problems and mental health showed consistent results across all three indicators. Table
5
6
7
8 3 shows the final results for all variables.
9

10 Important to note is that, after including control variables, there was a significant
11 effect of exposure to physical ground motion (PGA_{cum}) on all three health indicators:
12
13 more ground motion was associated with poorer health. The effect of time was also
14
15 significant: over time, health deteriorated. In the next step, we included damage to
16
17 housing. Importantly, the effect of ground motion was suppressed by the larger effects
18
19 of exposure to multiple damage on all health indicators (p 's<.01). This means that
20
21 damage better predicts health outcomes than ground motion. Having damage once had
22
23 no significant effect on any of the health indicators. Only participants with multiple
24
25 damages experienced negative health consequences.
26
27

28
29 In step 3, the significant 'multiple damage (vs no damage) X time' interaction reveals
30
31 that exposure to multiple damages is associated with a deterioration of health over time.
32
33
34 The inclusion of this interaction variable improved model fit.
35
36

37 To interpret the effects and assess their magnitude, we calculated odds ratios for
38
39 health measures at every time point, as well as the average impact of exposure over
40
41 time (Table 4). Inhabitants exposed to damage once are only marginally (and not
42
43 significantly) affected compared with a no-damage control group (averaged odds ratios
44
45 range from 1.10 to 1.20). Those exposed to damage multiple times are more likely to
46
47 report poor self-rated health (OR = 1.64, with a 95% confidence interval of 1.31;2.04),
48
49 more stress-related health symptoms (OR = 2.52 [1.89;3.38]) and less good mental
50
51
52
53
54
55
56
57
58
59
60

1
2
3 health (OR = 1.83 [1.40;2.39]) than those without damage. This indicates that damage
4
5 has a considerable impact on participants' health⁸.
6

7
8 The table also suggests that differences between groups increase over time.
9
10 Odds ratios for the difference between those with multiple damage and no damage are
11
12 considerably higher 21 months after first measurement for self-rated health (OR = 2.00
13
14 [1.57;2.55]), mental health (OR = 2.38 [1.78;3.21]) and stress related health symptoms
15
16 (OR = 3.36 [2.45;4.68]). In terms of relative risk, this means that those whose homes
17
18 have multiple damage at T5 are 1.60[1.37;1.86] times more likely to report poor health,
19
20 2.11 [1.63;2.74] times more likely to report negative mental health and 2.84 [2.14;3.76]
21
22 times more at risk of elevated levels of stress related health symptoms.
23
24
25

26 We also compared the weighted means of the ORs of control variables that are
27
28 known correlates of health (age, gender, level of education) to the effect of damage
29
30 (Figure 1). Across the three health measures, effect sizes (ORs) of damage are slightly
31
32 larger than those of education (for a high versus low level of education, the average
33
34 odds ratios over time are .53 [.41;.68] for self-rated health; OR = .58 [.42;.81] for mental
35
36 health; and OR = .56 [.41;.79] for stress-related health symptoms).
37
38
39
40

41 **DISCUSSION**

42
43
44 Natural and induced seismicity can have negative consequences for local
45
46 populations due to (acute or accumulated) health threats and irreversible changes to the
47
48 living environment. Yet, so far studies have not assessed the accumulated impact of
49
50 (the consequences of) induced seismicity on (psychosomatic) health *over time*.
51
52
53

54
55 ⁸ We also investigated whether women's health is affected differently by this stressor than men's, but as
56
57 evidenced in Table S2 in the supplementary materials, this is not the case.
58
59

1
2
3 Moreover, most studies lack a non-exposure control group. The present study aimed to
4 address these shortcomings by studying the impact of exposure to gas extraction (and
5 subsequent damage to housing), compared to a no-exposure control group, on health
6 over a time period of 21 months. Our study provides strong indications that exposure to
7 negative side-effects of induced seismicity (e.g., damage to people's homes) constitutes
8 an increasing health risk over time: We found that those exposed to multiple damage to
9 housing experienced more negative health consequences than those without damage.
10 Moreover, these effects increased over time. Results for exposure to ground motion
11 were comparable.
12
13
14
15
16
17
18
19
20
21
22
23

24 To our knowledge, this is the only study of the long-term impact of induced
25 seismicity on health. Therefore, we can only compare our results with the long-term
26 impacts of very different types of disaster - limiting comparability. For one, the
27 Chernobyl nuclear disaster: Study participants lived in a seriously contaminated area
28 approximately 50 miles from Chernobyl. 6.5 years post disaster, inhabitants were twice
29 as likely to have negative self-rated health (OR:2.25[1.96-2.58]) and psychological
30 distress (OR:1.93[1.69-2.22]), compared to a non-exposed control group[32].
31 Chernobyl clearly constitutes a very different type of disaster and health risk (radiation
32 exposure). The Brisbane floods were also very different in many respects (e.g., sudden
33 disaster onset; deaths) but with some comparable outcomes, such as considerable
34 damage to homes. 6-7 months post-disaster, those exposed to flooding were twice as
35 likely to report psychological distress compared to the non-exposed[33]. It appears that
36 the health impact of these very different and in many ways more 'acute' disasters are, in
37 terms of effect size, somewhat comparable to the health impact of the more chronic
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 exposure to lower-level seismicity caused by gas extraction. One potential reason for
4 the comparable effect sizes, is that our study focused not just on the environmental
5 effect (e.g., amount of damage in a particular area) but zoomed in on the subgroup who
6 were severely affected because they had multiple instances of damage to their own
7 home. We further speculate that the man-made nature of the hazard (the fact that
8 earthquakes are induced) may also enhance the impact on the population.
9
10
11
12
13
14
15
16

17 The present work also provides first time insights into the development of
18 (psychosomatic) health symptoms in response to chronic disaster. In the area of acute
19 disaster response, studies on longitudinal health impact reveal that distress decreases
20 over time[34, 35], implying recovery of victims. Yet looking at discussions comparing
21 chronic man-made (technological) disasters to acute natural disasters, we see reason to
22 expect long term health impacts of the gas extraction: It contains elements that have
23 been suggested as reasons for potential long-term health impact of technological
24 disasters: A strong element of culpability in causing disaster, concerns about damage
25 compensation after disaster and uncertainty regarding when disaster impact will end
26 (“the book is never closed”; p.148, [12]; [36-38]. In line with this work, our findings
27 suggest that for chronic disasters/hazards, negative effects can accumulate over time,
28 presumably because the recurrent threat leads to an accumulation of stress.
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43

44 **Limitations**

45
46 A potential limitation of this sample could be concerns about its
47 representativeness: For one, Attrition was 45.3% over time and younger respondents
48 were somewhat underrepresented. However, attrition was no different for the exposed
49 and non-exposed groups, unrelated to health outcomes, and all further analyses
50
51
52
53
54
55
56
57
58
59
60

1
2
3 suggest that neither attrition nor sample characteristics had any substantial influence on
4 results and conclusions drawn. Secondly, there might be an influence of confounding
5 variables. Yet we believe effect sizes are robust: 1. The exposed and control groups
6 were very similar regarding key population and geographical characteristics 2. Follow-
7 up analyses revealed no interactions between any of the population characteristics and
8 the effects of exposure.
9

10
11 Thirdly, responses could have been biased because participants knew the survey was
12 about the social impact of gas extraction. It is relevant here that an 'objective'
13 geographical exposure measure (peak ground acceleration) revealed comparable
14 health outcomes to self-reported exposure. Moreover, analyses on a cross-sectional
15 representative sample of residents (N=16340) in the 2016 health monitor of Statistics
16 Netherlands, the National Institute for Public Health and public health services found
17 comparable results. In this survey, the study intent was not clear.
18
19

20
21 One of the three health measures included, stress-related health symptoms, was
22 an adaptation of a previously validated symptoms list[39], shortened for this specific
23 study. Although the shortened version was not previously validated, it was
24 psychometrically sound. Also, patterns are comparable across health measures, two of
25 which are validated.
26
27

28
29 One of our exposure measures is self-reported damage. It is possible that
30 damage is perceived differently depending on people's health status. Importantly,
31 physical exposure to ground motion was associated with significant health effects. But
32 effects of damage were stronger. This could be because damage is a more precise and
33 proximate indicator of how individuals are affected by exposure, but also because of
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 recursive effects of (mental) health on perceived damage.
4

5 An important issue is generalizability: Is the situation in Groningen comparable to
6 other areas with induced seismicity (e.g., fracking, wastewater injections)? We can only
7 make reasoned inferences. Induced earthquakes are relatively common in energy
8 projects which involve injection[40]. A priori, similar health consequences could occur in
9 all sites in which populations are affected by induced earthquakes. Moreover, the
10 vulnerability of people exposed to seismicity is likely influenced by similar factors:
11 negative consequences are man-made and involve safety, health and social risks [12,
12 13]. In sum, although more research on the impact of induced seismicity is needed [41],
13 we suggest effects are likely to generalize beyond the Groningen case.
14
15
16
17
18
19
20
21
22
23
24
25

26 **Practical implications**

27 The consequences of induced seismicity pose challenges to decision-makers.
28 Benefits to the public good need to be balanced against the welfare of local populations
29 [21]. As projects involving induced seismicity rapidly grow, governments and businesses
30 face decisions whether to invest. Our work provides a case study of what occurs if
31 seismicity is not kept in check. It can increase awareness of the vulnerability of exposed
32 populations and provide important input for future decision making, monitoring and
33 contingency planning.
34
35
36
37
38
39
40
41
42
43

44 **Conclusion**

45 Recent years have seen a rise in induced seismicity. Little is known about the
46 (longitudinal) impact thereof on (psychosomatic) health. The present study is the first to
47 our knowledge evidencing the long-term impact of induced seismicity on health.
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 **Funding:** This study was funded by the National Coordinator Groningen. Award/grant
4 number: not applicable.
5

6
7 **Contributorship:** KS, BK, JR, JB, FO, FG and TP contributed to the research
8 questions and study design. JR and FO contributed to data collection. BK and TP
9 conducted statistical analyses. KS, BK and TP interpreted the results and wrote the
10 initial draft of the manuscript. All authors commented on the final draft of the manuscript.
11 BK and TP had full access to the data in the study and can take responsibility for the
12 integrity of the data and the accuracy of the data analysis.
13
14

15 **Conflict of Interest:** The authors declare that they have no conflict of interest.
16

17 **Ethical approval:** All procedures performed in studies involving human participants
18 were in accordance with the ethical standards of the ethical board of the department of
19 psychology of the University of Groningen, The Netherlands (research code ppo-015-
20 085).
21

22 **Informed consent:** Informed consent was obtained from all individual participants
23 included in the study.
24

25 **Data sharing statement:** Data collected for this study are not available in order to
26 guarantee anonymity of participants.
27
28
29
30
31
32

Table 1.

List of definitions

Conventional gas extraction	Extraction through drilling in deep subsoil reservoirs without the injection of chemical liquids.
Fracking	A well stimulation technique in which a rock is fractured by a pressured liquid.
Induced seismicity	Seismic events that are a result of human activity.
Natural seismicity	Seismic events that have a natural cause (e.g., volcanic eruption).
Peak ground acceleration	Measure of the largest increase in ground motion, recorded by a particular station during an earthquake.
Psychosomatic health	Health outcomes involving both mind and body.
Richter scale	Measure of strength of earthquakes with a logarithmic scale.
Shale gas	A natural gas that is trapped in fine grained sediment in rock.
Unconventional gas extraction	Gas reservoirs that require a special stimulation technique to extract gas (e.g., by injecting large quantities of partly chemical fluids underground).

Table 2

Demographic characteristics of participants participating in separate measurements: total number of participants participating in that measurement, decline of number of participants participating as compared to the number of participants participating at T1, mean age, distribution of level of education, distribution of personal exposure to damage due to gas extraction, distribution of gender, and amount of participants that completed the three health measures in that measurement. Netherlands 2016-2017

	T1	T2	T3	T4	T5
	Feb '16	June '16	Nov '16	Apr '17	Nov '17
Total N	3934	3153	2638	2351	2150
Attrition (compared to T1)	-	19.9%	32.9%	40.2%	45.3%
Age (mean)	56.54	57.74	57.72	58.90	59.98
Level of education (N)					
Low	968 (24.6%)	772 (24.5%)	616 (23.4%)	589 (25.1%)	535 (24.9%)
Middle	1252 (31.8%)	970 (30.8%)	815 (30.9%)	713 (30.3%)	639 (29.7%)
High	1533 (39.0%)	1238 (39.3%)	1068 (40.5%)	944 (40.2%)	852 (39.6%)
Gender (N)					
Male	1967 (50.0%)	1547 (49.1%)	1306 (49.5%)	1182 (50.3%)	1068 (49.7%)
Female	1849 (47.0%)	1480 (46.9%)	1231 (46.7%)	1097 (46.7%)	990 (46.0%)
Exposure to damage (N)					
None	1477 (37.5%)	1204 (38.2%)	1027 (38.9%)	910 (38.7%)	846 (39.3%)
One time	913 (23.2%)	626 (19.9%)	554 (21.0%)	505 (21.5%)	459 (21.3%)
Multiple	1057 (26.9%)	1055 (33.5%)	940 (35.6%)	775 (33.0%)	736 (34.2%)
Perceived health (N)	3821 (97.1%)	-	2540 (96.3%)	2206 (93.8%)	2059 (95.8%)
Stress related health symptoms (N)	3767 (95.8%)	-	2533 (96.0%)	2206 (93.8%)	2045 (95.1%)
Mental health (N)	3711 (94.3%)	2819 (89.4%)	2501 (94.8%)	2179 (92.7%)	2021 (94.0%)

Table 3

Results of multilevel conditional growth models: *Unstandardized parameter estimates and standard errors for the association between time, damage, and the interaction between time and damage on perceived health, stress-related health symptoms, and mental health – adjusted for gender, age, level of education and ground motion (cumulative PGA). Netherlands 2016-2017.*

	Perceived health	Stress-related health symptoms ¹	Mental health
Gender	-0.05* (0.02)	-5.40*** (0.49)	-2.68*** (0.46)
Age	-0.01*** (0.001)	-0.02 (0.02)	0.07*** (0.02)
Level of education (middle)	0.08* (0.03)	0.61 (0.67)	1.01 (0.62)
Level of education (high)	0.24*** (0.03)	3.02*** (0.63)	2.94*** (0.59)
Cumulative PGA	-0.001 (0.004)	0.03 (0.09)	-0.01 (0.08)
Time	-0.01 (0.01)	-0.25* (0.13)	-0.49*** (0.15)
Damage (one time)	-0.01 (0.03)	-0.46 (0.75)	-0.27 (0.63)
Damage (multiple)	-0.12*** (0.03)	-4.31*** (0.76)	-3.35*** (0.65)
Time * Damage (one time)	-0.02 (0.01)	-0.13 (0.20)	-0.07 (0.24)
Time * Damage (multiple)	-0.03*** (0.01)	-0.45* (0.19)	-0.60** (0.23)
Constant	3.86*** (0.03)	80.19*** (0.67)	77.78*** (0.60)
Observations	10,256	9,100	9,686
Log Likelihood	-10,104.58	-36,205.01	-38,020.51
Akaike Inf. Crit.	20,239.16	72,440.02	76,071.02
Bayesian Inf. Crit.	20,347.69	72,546.76	76,178.69

Note. *p<0.05; **p<0.01; ***p<0.001

1. Stress-related health symptoms were reverse-coded such that higher levels indicate less stress

Table 4

Proportion of participants who have poor health and OR of participants who have poor health with damage (compared to those with no damage) across measurements, with 95% confidence intervals – adjusted for age, gender and level of education. Netherlands 2016-2017

Measurement	Damage	Percentage poor health	Odds ratio
Self-rated health			
T1	None	22.2% [19.9%;24.5%]	-
	One time	22.5% [19.6%;25.4%]	1.02 [0.82;1.26]
	Multiple	25.6% [22.7%;28.4%]	1.21 [0.99;1.47]
T3	None	21.6% [18.8%;24.3%]	-
	One time	24.4% [20.5%;28.3%]	1.17 [0.90;1.53]
	Multiple	32.4% [29.2%;35.7%]	1.75 [1.41;2.18]
T4	None	21.3% [18.4%;24.2%]	-
	One time	30.0% [25.7%;34.4%]	1.60 [1.22;2.09]
	Multiple	35.5% [31.8%;39.2%]	2.06 [1.63;2.61]
T5	None	23.6% [20.3%;26.9%]	-
	One time	27.5% [22.9%;32.1%]	1.23 [0.92;1.65]
	Multiple	38.0% [34.0%;42.0%]	2.00 [1.57;2.55]
Weighted average	None	22.1% [19.4%;24.9%]	-
	One time	25.6% [21.8%;29.4%]	1.20 [0.93;1.55]
	Multiple	31.8% [28.5%;35.2%]	1.64 [1.31;2.04]
Symptoms			
T1	None	9.2% [7.7%;10.8%]	-
	One time	10.0% [7.9%;12.1%]	1.09 [0.81;1.47]
	Multiple	17.3% [14.9%;19.7%]	2.08 [1.62;2.68]
T3	None	7.1% [5.5%;8.8%]	-
	One time	6.5% [4.3%;8.6%]	0.90 [0.58;1.37]
	Multiple	13.7% [11.4%;16.1%]	2.09 [1.55;2.85]
T4	None	8.1% [6.2%;10.0%]	-
	One time	9.4% [6.7%;12.1%]	1.18 [0.78;1.75]
	Multiple	21.8% [18.7%;25.0%]	3.24 [2.40;4.42]
T5	None	7.1% [5.3%;9.0%]	-
	One time	9.1% [6.3%;11.9%]	1.30 [0.84;1.99]
	Multiple	20.3% [17.0%;23.5%]	3.36 [2.45;4.68]
Weighted average	None	8.0% [6.4%;9.8%]	-
	One time	8.8% [6.5%;11.2%]	1.10 [0.75;1.60]
	Multiple	18.0% [15.3%;20.7%]	2.52 [1.89;3.38]
Mental health			

1				
2				
3	T1	None	8.5% [7.0%;10.0%]	-
4		One time	9.0% [7.0%;10.9%]	1.06 [0.78;1.43]
5		Multiple	12.4% [10.3%;14.5%]	1.53 [1.18;1.98]
6				
7	T2	None	8.5% [6.8%;10.2%]	-
8		One time	9.2% [6.9%;11.6%]	1.09 [0.77;1.54]
9		Multiple	18.1% [15.6%;20.7%]	2.40 [1.86;3.13]
10				
11	T3	None	11.1% [9.0%;13.2%]	-
12		One time	12.0% [9.2%;14.9%]	1.10 [0.79;1.51]
13		Multiple	14.5% [12.1%;16.9%]	1.36 [1.04;1.77]
14				
15	T4	None	11.9% [9.6%;14.1%]	-
16		One time	11.8% [8.9%;14.7%]	0.99 [0.71;1.38]
17		Multiple	20.3% [17.2%;23.4%]	1.9 [1.46;2.47]
18				
19	T5	None	9.0% [6.9%;11.1%]	-
20		One time	12.5% [9.3%;15.7%]	1.44 [0.99;2.07]
21		Multiple	19.1% [15.9%;22.2%]	2.38 [1.78;3.21]
22				
23	Weighted average	None	9.7% [7.8%;11.5%]	-
24		One time	10.6% [8.1%;13.2%]	1.11 [0.80;1.55]
25		Multiple	16.4% [13.8%;19.0%]	1.83 [1.40;2.39]
26				
27				
28				
29				
30				
31				
32				
33				
34				

Note. Scores were categorised as low health as follows: 1) very poor, poor, or fair perceived health; 2) a score below 60 for stress related health symptoms, and 3) a score below 60 for mental health.

REFERENCES

- 1 Konkel L. In the Neighborhood of 18 Million: Estimating How Many People Live Near Oil and Gas Wells, *Environ Health Perspect* 2017;125:UNSP 124003 doi:10.1289/EHP2553 [published Online First: DEC].
- 2 U.S. Energy Information Administration. United States Shale gas reserves per state. 2017;2019.
- 3 Dai W, Chen L, Lai Z, et al. The incidence of post-traumatic stress disorder among survivors after earthquakes: A systematic review and meta-analysis, *BMC Psychiatry* 2016;16.
- 4 Neria Y, Nandi A, Galea S. Post-traumatic stress disorder following disasters: A systematic review, *Psychol Med* 2008;38:467-80 doi:10.1017/S0033291707001353.
- 5 Beaglehole B, Mulder RT, Frampton CM, et al. Psychological distress and psychiatric disorder after natural disasters: systematic review and meta-analysis, *The British Journal of Psychiatry* 2018;213:716-22.
- 6 Goldmann E, Galea S. Mental health consequences of disasters, *Annu Rev Public Health* 2014;35:169-83.
- 7 Galea S, Nandi A, Vlahov D. The epidemiology of post-traumatic stress disorder after disasters, *Epidemiol Rev* 2005;27:78-91.
- 8 Norris FH, Friedman MJ, Watson PJ. 60,000 disaster victims speak: Part II. Summary and implications of the disaster mental health research, *Psychiatry: Interpersonal and biological processes* 2002;65:240-60.
- 9 Rubonis AV, Bickman L. Psychological impairment in the wake of disaster: The disaster–psychopathology relationship. *Psychol Bull* 1991;109:384.
- 10 Keranen KM, Weingarten M. Induced Seismicity, *Annual Review of Earth and Planetary Sciences, Vol 46* 2018;46:149-74 doi:10.1146/annurev-earth-082517-010054.
- 11 van der Elst, Nicholas J., Page MT, Weiser DA, et al. Induced earthquake magnitudes are as large as (statistically) expected, *Journal of Geophysical Research-Solid Earth* 2016;121:4575-90 doi:10.1002/2016JB012818 [published

- 1
2
3 Online First: JUN].
4
5 12 Couch SR, Kroll-Smith JS. The chronic technical disaster: Toward a social scientific
6 perspective, *Social Science Quarterly* 1985;66:564.
7
8 13 Sangaramoorthy T, Jamison AM, Boyle MD, et al. Place-based perceptions of the
9 impacts of fracking along the Marcellus Shale, *Soc Sci Med* 2016;151:27-37.
10
11 14 Rabinowitz PM, Slizovskiy IB, Lamers V, et al. Proximity to Natural Gas Wells and
12 Reported Health Status: Results of a Household Survey in Washington County,
13 Pennsylvania, *Environ Health Perspect* 2015;123:21-6 doi:10.1289/ehp.1307732.
14
15 15 Steinzor N, Subra W, Sumi L. Investigating links between shale gas development
16 and health impacts through a community survey project in Pennsylvania. *New
17 solutions : a journal of environmental and occupational health policy : NS*
18 2013;23:55-83 doi:10.2190/NS.23.1.e.
19
20 16 Tustin AW, Hirsch AG, Rasmussen SG, et al. Associations between Unconventional
21 Natural Gas Development and Nasal and Sinus, Migraine Headache, and
22 Fatigue Symptoms in Pennsylvania, *Environ Health Perspect* 2017;125:189-97
23 doi:10.1289/EHP281.
24
25 17 Weinberger B, Greiner LH, Walleigh L, et al. Health symptoms in residents living
26 near shale gas activity: A retrospective record review from the Environmental
27 Health Project. *Preventive medicine reports* 2017;8:112-5
28 doi:10.1016/j.pmedr.2017.09.002.
29
30 18 Wilson MP, Foulger GR, Gluyas JG, et al. HiQuake: The human-induced earthquake
31 database, *Seismol Res Lett* 2017;88:1560-5.
32
33 19 Aczel MR, Makuch KE. Shale, Quakes, and High Stakes: Regulating Fracking-
34 Induced Seismicity in Oklahoma, USA and Lancashire, UK, *Case Studies in the
35 Environment* 2019.
36
37 20 Keranen KM, Weingarten M, Abers GA, et al. Sharp increase in central Oklahoma
38 seismicity since 2008 induced by massive wastewater injection, *Science*
39 2014;345:448-51 doi:10.1126/science.1255802 [published Online First: JUL 25].
40
41 21 Fleming RC, Reins L. Shale gas extraction, precaution and prevention: A
42 conversation on regulatory responses, *Energy Research & Social Science*
43 2016;20:131-41 doi:10.1016/j.erss.2016.05.013 [published Online First: OCT].
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3 22 Vlek C. Rise and reduction of induced earthquakes in the Groningen gas field, 1991-
4 2018: statistical trends, social impacts, and policy change, *Environ Earth Sci*
5 2019;78:59 doi:10.1007/s12665-019-8051-4 [published Online First: FEB].
6
7
8 23 Dutch Safety Board. Earthquake risks in Groningen. Research concerning the role
9 population safety played in decision making procedures about gas extraction
10 (1959-2014) , 2015.
11
12
13 24 Postmes T, Stroebe K, Richardson J, et al. Consequences of ground motion for the
14 Groningen population: Experienced safety, health and future perspective 2016-
15 2017. *University of Groningen* 2018.
16
17
18 25 Geurts C, Steenbergen R. Note for the Dutch State Supervision of Mines: The
19 relation between Peak Ground Acceleration and the risk of damage for induced
20 earthquakes in Groningen. *The Netherlands Organisation for Applied Scientific*
21 *Research* 2016.
22
23
24 26 Pappas G. Health interview surveys: Towards international harmonization of
25 methods and instruments - deBruin,A, Picavet,HSJ, Nossikoy,A, *Soc Sci Med*
26 1997;44:1431-2 doi:10.1016/S0277-9536(97)84078-6 [published Online First:
27 MAY].
28
29
30 27 Ware JE, Gandek B, IQOLA Project. Overview of the SF-36 Health Survey and the
31 International Quality of Life Assessment (IQOLA) Project, *J Clin Epidemiol*
32 1998;51:903-12 doi:10.1016/S0895-4356(98)00081-X [published Online First:
33 NOV].
34
35
36 28 Van den Berg B, Yzermans CJ, Van der Velden, Peter G., et al. Risk Factors for
37 Unexplained Symptoms After a Disaster: A Five-Year Longitudinal Study in
38 General Practice, *Psychosomatics* 2009;50:69-77 doi:10.1176/appi.psy.50.1.69.
39
40
41 29 Berwick DM, Murphy JM, Goldman PA, et al. Performance of a five-item mental
42 health screening test. *Med Care* 1991.
43
44
45 30 Raudenbush SW, Bryk AS. Hierarchical linear models: Applications and data
46 analysis methods: Sage 2002.
47
48
49 31 Rumpf H, Meyer C, Hapke U, et al. Screening for mental health: validity of the MHI-5
50 using DSM-IV Axis I psychiatric disorders as gold standard, *Psychiatry Res*
51 2001;105:243-53.
52
53
54
55
56
57
58
59
60

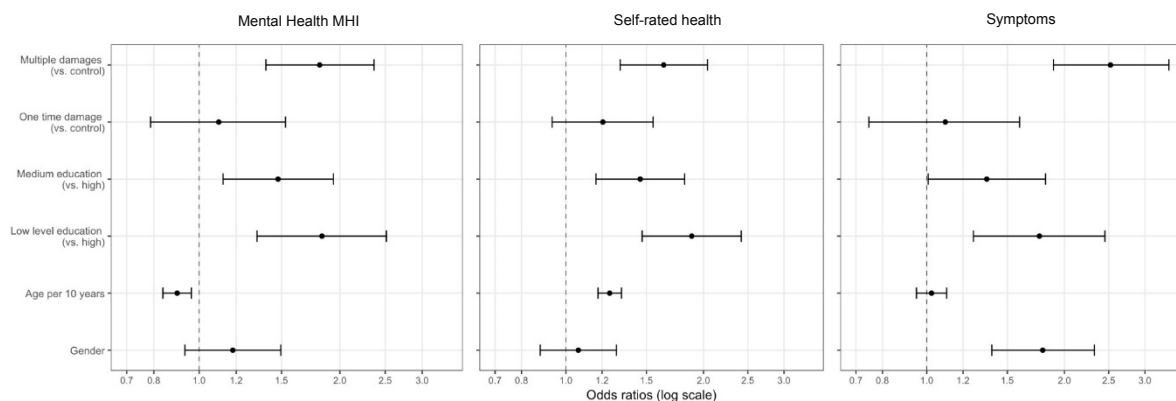
- 1
2
3 32 Havenaar J, Rumyantzeva G, Kasyanenko A, et al. Health effects of the Chernobyl
4 disaster: Illness or illness behavior? A comparative general health survey in two
5 former Soviet regions, *Environ Health Perspect* 1997;105:1533-7
6
7 doi:10.2307/3433666 [published Online First: DEC].
8
9
10 33 Alderman K, Turner LR, Tong S. Assessment of the Health Impacts of the 2011
11 Summer Floods in Brisbane, *Dis Med Public Health Prep* 2013;7:380-6
12
13 doi:10.1017/dmp.2013.42 [published Online First: AUG].
14
15 34 Lowell A, Suarez-Jimenez B, Helpman L, et al. 9/11-related PTSD among highly
16 exposed populations: a systematic review 15 years after the attack, *Psychol Med*
17
18 2018;48:537-53 doi:10.1017/S0033291717002033 [published Online First: MAR].
19
20 35 van der Velden, Peter G., Wong A, Boshuizen HC, et al. Persistent mental health
21 disturbances during the 10years after a disaster: Four-wave longitudinal
22 comparative study, *Psychiatry Clin Neurosci* 2013;67:110-8
23
24 doi:10.1111/pcn.12022 [published Online First: FEB].
25
26
27 36 Baum A. Implications of psychological research on stress and technological
28 accidents. *Am Psychol* 1993;48:665.
29
30
31 37 Picou JS. The “talking circle” as sociological practice: Cultural transformation of
32 chronic disaster impacts, *Sociological Practice* 2000;2:77-97.
33
34 38 Picou JS, Marshall BK, Gill DA. Disaster, litigation, and the corrosive community,
35
36 *Social forces* 2004;82:1493-522.
37
38 39 van den Berg B, Grievink L, Yzermans J, et al. Medically unexplained physical
39 symptoms in the aftermath of disasters, *Epidemiol Rev* 2005;27:92-106
40
41 doi:10.1093/epirev/mxi001.
42
43 40 Ellsworth WL. Injection-induced earthquakes, *Science* 2013;341:1225942.
44
45 41 Hirsch JK, Smalley KB, Selby-Nelson EM, et al. Psychosocial Impact of Fracking: a
46 Review of the Literature on the Mental Health Consequences of Hydraulic
47 Fracturing, *International Journal of Mental Health and Addiction* 2018;16:1-15
48
49 doi:10.1007/s11469-017-9792-5 [published Online First: FEB].
50
51
52
53
54
55
56
57
58
59
60

1
2
3 Figure 1. Weighted average odds ratios.
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For peer review only

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Figure 1. Weighted average odds ratios.

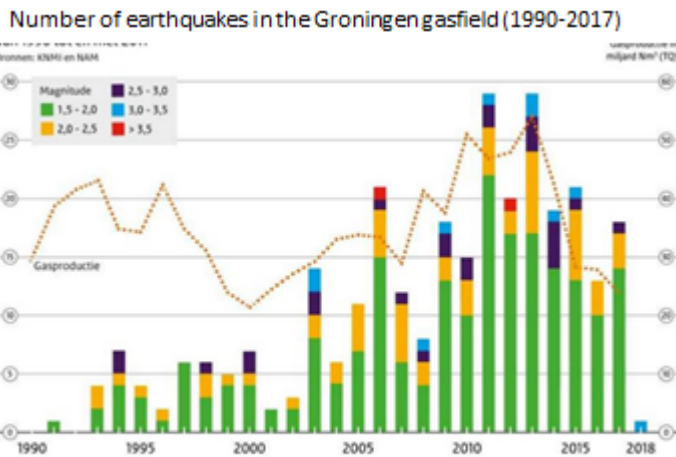


For peer review only

Supplementary materials

Seismicity in the Groningen gasfield

Figure S1: Number of earthquakes and volume of gas production in the Groningen gasfield:



The volume of gas production in the subsoil of Groningen is presented as a dotted line in Figure 2. The number of earthquakes magnitude 2 or higher increased from 2003 onwards. The earthquake of August 2012 in the village of Huizinge (magnitude 3,6 on Richter scale) was a landmark event that caused unrest and great concern among the population in the province of Groningen. It was the heaviest earthquake measured in the province. The magnitude of earthquakes is recorded by the Dutch national borehole network, the regional accelerometer network and all additional seismic stations in the south of the Netherlands. European seismic stations reported the event at epicentral distances up to 800 km (Dost and Kraaiipoel, 2012).

410,000 residents of the province of Groningen are exposed to these induced earthquakes: they live in a postcode area where damage has been recognized by the oil company responsible (NAM, a joint venture of Shell and Exxon). Of these, 134,363 adults report having damage to their property (Postmes et al., 2017). Of these 68,343 report having damage multiple times.

Looking worldwide, there are 1174 locations in which induced seismicity is taking place. 11% of seismicity is due to conventional oil or gas extraction (see inducedearthquakes.org/)

References

Dost B and Kraaiipoel D. The August 16, 2012 earthquake near Huizinge in Groningen province. Royal Dutch Meteorological Institute, 2013.

Postmes, T., Stroebe, K., Richardson, J., LeKander, B., Oldersma, F., Broer, J. & Greven, F. (2018). Gevolgen van bodembeweging voor Groningers: Ervaren veiligheid, gezondheid en toekomstperspectief 2016-2017. Groningen: Heymans Instituut, Rijksuniversiteit Groningen.

Table S1

Demographic characteristics of participants completing separate measurements per level of damage: total sample size, mean age, distribution of level of education, distribution of level of damage, distribution of gender, and amount of participants that completed the health measures. Netherlands 2016-2017

Damage to house at T1		T1 Feb '16	T2 June '16	T3 Nov '16	T4 Apr '17	T5 Nov '17	
None	Total N	1477	1166	968	886	801	
	Age (mean)	57.67	59.13	59.13	60.28	61.48	
	Level of education (N)	Low	430	340	266	267	238
		Middle	460	351	290	255	226
		High	562	453	396	349	324
	Gender (N)	Male	794	621	515	471	427
		Female	683	545	453	415	374
	Perceived health (N)	1467	-	934	835	784	
	Stress related health symptoms (N)	1452	-	937	836	780	
Mental health (N)	1432	1048	920	828	769		
One time	Total N	913	730	608	559	490	
	Age (mean)	58.32	58.87	58.81	60.06	60.86	
	Level of education (N)	Low	237	191	155	143	131
		Middle	295	235	195	182	159
		High	363	295	250	227	193
	Gender (N)	Male	505	398	345	323	279
		Female	407	332	263	236	211
	Perceived health (N)	907	-	587	521	464	
	Stress related health symptoms (N)	894	-	584	522	463	
Mental health (N)	895	666	581	517	456		
Multiple	Total N	1057	825	704	609	558	
	Age (M)	54.06	55.57	55.60	56.71	57.70	
	Level of education (N)	Low	215	168	133	120	110
		Middle	381	289	246	213	188
		High	445	356	315	268	253
	Gender (N)	Male	493	385	323	284	269
		Female	563	440	381	325	289
	Perceived health (N)	1048	-	683	578	537	
	Stress related health symptoms (N)	1041	-	675	577	530	
Mental health (N)	1018	739	674	570	528		

Table S2

Unstandardized regression parameter estimates and standard errors for the association between time, damage, and the interaction between time and damage on perceived health, stress-related health symptoms, and mental health, and the interaction between gender and damage on perceived health, stress-related health symptoms, and mental health – adjusted for gender, age, level of education and ground motion (cumulative PGA). Netherlands 2016-2017.

	Perceived health	Stress-related health symptoms ¹	Mental health
Gender	-0.07 (0.04)	-5.08*** (0.75)	-2.81*** (0.70)
Age	-0.01*** (0.001)	-0.02 (0.02)	0.07*** (0.02)
Level of education (middle)	0.08* (0.03)	0.62 (0.67)	0.99 (0.62)
Level of education (high)	0.23*** (0.03)	3.03*** (0.63)	2.92*** (0.59)
Cumulative PGA	-0.001 (0.004)	0.03 (0.09)	-0.01 (0.08)
Time	-0.01 (0.01)	-0.25* (0.13)	-0.49*** (0.15)
Damage (one time)	-0.02 (0.04)	-0.19 (0.93)	-0.05 (0.81)
Damage (multiple)	-0.14** (0.04)	-4.04*** (0.95)	-3.79*** (0.84)
Time * Damage (one time)	-0.02 (0.01)	-0.13 (0.20)	-0.07 (0.24)
Time * Damage (multiple)	-0.03*** (0.01)	-0.45* (0.19)	-0.60** (0.23)
Gender * Damage (one time)	0.03 (0.06)	-0.58 (1.21)	-0.51 (1.13)
Gender * Damage (multiple)	0.04 (0.05)	-0.55 (1.15)	0.85 (1.07)
Constant	3.87*** (0.03)	80.04*** (0.73)	77.86*** (0.65)
Observations	10,256	9,100	9,686
Log Likelihood	-10,104.34	-36,204.85	-38,019.84
Akaike Inf. Crit.	20,242.68	72,443.70	76,073.68
Bayesian Inf. Crit.	20,365.69	72,564.67	76,195.71

Note. * p<0.05; ** p<0.01; *** p<0.001

1. Stress-related health symptoms were reverse-coded such that higher levels indicate less stress

STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No.	Recommendation	Page No.	Relevant text from manuscript
Title and abstract	1	(a) Indicate the study’s design with a commonly used term in the title or the abstract	1/2	Title is mentioned on page 1
		(b) Provide in the abstract an informative and balanced summary of what was done and what was found	2	
Introduction				
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	4/5	
Objectives	3	State specific objectives, including any prespecified hypotheses	5/6	The present work was designed to address the lack of information regarding the long-term impact of induced seismicity for residents: It studies the longitudinal (psychosomatic) health impact of induced seismicity on a group exposed to the consequences of seismicity (damage to housing) versus a control group not exposed to these consequences.” “The present study is novel in charting the chronic impact of exposure to damage on health over a time period of almost two years, on a large sample. We tested the following hypotheses: 1. Exposure versus

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

non-exposure will have a negative impact on (psychosomatic) health outcomes. 2. Increases in exposure are related to poorer health outcomes.”

Methods

Study design	4	Present key elements of study design early in the paper	5-8	
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	6-8	“A stratified random sample was drawn of 25000 residents of the province of Groningen, aged 16 and over, from the official municipal population records which is a complete register of all legal residents. Sampling occurred in areas where damage is reported and from outlying areas where this is not the case. Postal-code areas that were rural and strongly affected by damage were oversampled . Residents received letters with personal login codes and one reminder. Eighteen percent (N=4577) signed up for the study, and later received invitations to all questionnaires. Of these 4577, 86% (3934) filled out the first questionnaire.”; “Questionnaires were sent via

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

an email link or by post. A reminder was sent after 2 weeks. Participants (T1: N=3934; T5: N=2150) completed measures at 5 time points during 2 years (T1: February 2016, T2: June 2016; T3: November 2016; T4: April 2017; T5: November 2017; see Table 2).

Participants	6	<p>(a) <i>Cohort study</i>—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up</p> <p><i>Case-control study</i>—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls</p> <p><i>Cross-sectional study</i>—Give the eligibility criteria, and the sources and methods of selection of participants</p> <hr/> <p>(b) <i>Cohort study</i>—For matched studies, give matching criteria and number of exposed and unexposed</p> <p><i>Case-control study</i>—For matched studies, give matching criteria and the number of controls per case</p>	7	
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	8-10	
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	8-10	
Bias	9	Describe any efforts to address potential sources of bias	10	Analyses controlled for age, gender and education level. Analyses were weighted to correct for sampling effects of age, gender and degree of exposure of postal-code areas . The weights were developed to

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

counteract any potential
distortive effect due to age
composition, among others
(e.g., because younger people
were underrepresented, see
results section). We report the
weighted results. The
unweighted results were very
similar.

Study size	10	Explain how the study size was arrived at	7
------------	----	---	---

Continued on next page

Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	10-11	
Statistical methods	12	(a) Describe all statistical methods, including those used to control for confounding	10-11	
		(b) Describe any methods used to examine subgroups and interactions	10-11	
		(c) Explain how missing data were addressed	10	Participants with missing data on the health indices were retained, as multilevel modelling is robust to missingness in estimation of model outcomes. See Table 2 for an overview of the number of participants completing each health measure per time point.
		(d) <i>Cohort study</i> —If applicable, explain how loss to follow-up was addressed <i>Case-control study</i> —If applicable, explain how matching of cases and controls was addressed <i>Cross-sectional study</i> —If applicable, describe analytical methods taking account of sampling strategy	11-12	There was attrition during the study. Dropout characteristics revealed no differences between exposed vs. control groups and no association between dropout and health. Analyses showed no indications that attrition influenced any of the effects reported below. Over time, the average age of participants increased, as young people tended to have a higher likelihood of dropout. It is important to note that additional analyses found no significant interaction effect between age and exposure, suggesting that the effects of exposure were age-independent. Because the sample was not entirely representative and attrition relatively high, we carefully checked the potential consequences thereof and found no indications this influenced results.
		(e) Describe any sensitivity analyses		

Results

Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed		Table 2
		(b) Give reasons for non-participation at each stage	N/A	
		(c) Consider use of a flow diagram	N/A	
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders		Table 2
		(b) Indicate number of participants with missing data for each variable of interest	N/A	
		(c) <i>Cohort study</i> —Summarise follow-up time (eg, average and total amount)		
Outcome data	15*	<i>Cohort study</i> —Report numbers of outcome events or summary measures over time		
		<i>Case-control study</i> —Report numbers in each exposure category, or summary measures of exposure		
		<i>Cross-sectional study</i> —Report numbers of outcome events or summary measures		
Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	13-14	Table 3/4
		(b) Report category boundaries when continuous variables were categorized	11	Tables 3/4
		(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period		

Continued on next page

Other analyses	1	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	
	7		
Discussion			
Key results	1	Summarise key results with reference to study objectives	15
	8		
Limitations	1	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss	16-17
	9	both direction and magnitude of any potential bias	
Interpretation	2	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of	16
	0	analyses, results from similar studies, and other relevant evidence	
Generalisability	2	Discuss the generalisability (external validity) of the study results	17-18
	1		
Other information			
Funding	2	Give the source of funding and the role of the funders for the present study and, if applicable, for the	19
	2	original study on which the present article is based	

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at <http://www.plosmedicine.org/>, Annals of Internal Medicine at <http://www.annals.org/>, and Epidemiology at <http://www.epidem.com/>). Information on the STROBE Initiative is available at www.strobe-statement.org.

BMJ Open

Chronic disaster impact: the long-term psychological and physical health consequences of housing damage due to induced earthquakes

Journal:	<i>BMJ Open</i>
Manuscript ID	bmjopen-2020-040710.R2
Article Type:	Original research
Date Submitted by the Author:	07-Apr-2021
Complete List of Authors:	Stroebe, Katherine; Rijksuniversiteit Groningen, Social Psychology Kanis, Babet; Rijksuniversiteit Groningen, Social Psychology Richardson, Justin; Rijksuniversiteit Groningen, Social Psychology Oldersma, Frans; Department for Statistics and Research, Municipality of Groningen, Groningen, Netherlands Broer, Jan; Municipal Health Services Groningen, ABPG; Greven, Frans; Municipal Health Services Groningen, the Netherlands, Department of Environmental Health Postmes, Tom; Rijksuniversiteit Groningen, Social Psychology
Primary Subject Heading:	Public health
Secondary Subject Heading:	Mental health, Public health
Keywords:	MENTAL HEALTH, EPIDEMIOLOGY, PUBLIC HEALTH

SCHOLARONE™
Manuscripts



I, the Submitting Author has the right to grant and does grant on behalf of all authors of the Work (as defined in the below author licence), an exclusive licence and/or a non-exclusive licence for contributions from authors who are: i) UK Crown employees; ii) where BMJ has agreed a CC-BY licence shall apply, and/or iii) in accordance with the terms applicable for US Federal Government officers or employees acting as part of their official duties; on a worldwide, perpetual, irrevocable, royalty-free basis to BMJ Publishing Group Ltd ("BMJ") its licensees and where the relevant Journal is co-owned by BMJ to the co-owners of the Journal, to publish the Work in this journal and any other BMJ products and to exploit all rights, as set out in our [licence](#).

The Submitting Author accepts and understands that any supply made under these terms is made by BMJ to the Submitting Author unless you are acting as an employee on behalf of your employer or a postgraduate student of an affiliated institution which is paying any applicable article publishing charge ("APC") for Open Access articles. Where the Submitting Author wishes to make the Work available on an Open Access basis (and intends to pay the relevant APC), the terms of reuse of such Open Access shall be governed by a Creative Commons licence – details of these licences and which [Creative Commons](#) licence will apply to this Work are set out in our licence referred to above.

Other than as permitted in any relevant BMJ Author's Self Archiving Policies, I confirm this Work has not been accepted for publication elsewhere, is not being considered for publication elsewhere and does not duplicate material already published. I confirm all authors consent to publication of this Work and authorise the granting of this licence.

1
2
3
4
5
6 Chronic disaster impact: the long-term psychological and physical health consequences
7 of housing damage due to induced earthquakes
8

9 Stroebe, K.¹, Kanis, B.¹, Richardson, J.¹, Oldersma, F.², Broer, J.³, Greven, F.³ & Postmes, T.¹,
10
11

12
13 1. University of Groningen, Faculty of Behavioral and Social Sciences, Groningen,
14 Netherlands

15 2. Department for Statistics and Research, Municipality of Groningen, Groningen,
16 Netherlands

17 3. Municipal Health Services Groningen, Groningen, Netherlands
18
19

20 Corresponding author: Katherine Stroebe, k.e.stroebe@rug.nl, +313636509
21
22

Abstract

Objectives: To evaluate the long-term (psychosomatic) health consequences of man-made earthquakes compared to a non-exposure control group. Exposure was hypothesized to have an increasingly negative impact on health outcomes over time.

Setting — Large scale gas extraction in the Netherlands causing earthquakes and considerable damage.

Participants — A representative sample of inhabitants randomly selected from municipal population records; contacted 5 times during 21 months (T1:N=3934; T5:N=2150; mean age: 56.54; 50%males; At T5, N=846 (39.3%) had no, 459 (21.3%) once, and 736 (34.2%) repeated damages.

Main measures — (Psychosomatic) health outcomes: Self rated health and Mental Health Inventory (both: validated; Short Form Health Survey); stress related health symptoms (shortened version of previously validated symptoms list) Independent variable: Exposure to the consequences of earthquakes assessed via physical (Peak Ground Acceleration, PGA) and personal exposure (damage to housing: none, once, repeated).

Results: Exposure to induced earthquakes has negative health consequences especially for those whose homes were damaged repeatedly. Compared to a no-damage control group, repeated damage was associated with lower self-rated health (OR:1.64), mental health (OR:1.83) and more stress-related health symptoms (OR:2.52). Effects increased over time: In terms of relative risk, by T5, those whose homes had repeated damage were respectively 1.60 and 2.11 times more likely to report poor health and negative mental health and 2.84 times more at risk of elevated stress related health symptoms. Results for physical exposure were comparable.

Conclusion

This is the first study to provide evidence that induced earthquakes can have negative health consequences for inhabitants over time. It identifies the subpopulation particularly at risk: people with repeated damages who have experienced many earthquakes. Findings can have important implications for the prevention of negative health consequences of induced earthquakes.

1
2
3 Keywords: induced earthquakes; seismicity; longitudinal; psychosomatic health, gas extraction
4
5

6 **Strengths and limitations**
7

- 8 ● The present study employs a longitudinal panel design with 5 measurement
9 points to study (pschosomatic) health consequences of manmade earthquakes
10 caused by gas extraction
11
12 ● The study has an exposed (residents with damage to housing) and a non-
13 exposed (residents with no damage) control group
14
15 ● Two health measures (self-rated health; Mental Health Inventory) were
16 previously validated, the third was an adaptation of a previously validated
17 symptoms list
18
19 ● Younger respondents were somewhat underrepresented in our sample
20
21 ● There was 45.3% attrition over time but attrition was no different for the exposed
22 versus non-exposed groups and was unrelated to health outcomes.
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

INTRODUCTION

Recent years have seen a rise in induced seismicity due to human activities such as fracking, mining or gas extraction. This development is expected to continue. While smaller in magnitude than natural seismicity, induced seismicity can expose populations to considerable physical (e.g., damage to housing) and social risks (e.g., conflicts between residents and institutions). Moreover, this exposure is recurrent and chronic over time. While there is some insight into the long-term health risks of naturally occurring seismicity, little is known about the impact of induced seismicity. Given the increased use of energy technologies associated with seismicity, also in densely populated areas, knowledge of its health impact is important [1, 2] (see also Table 1 for definitions of gas-extraction related terminology).

Naturally occurring seismicity is associated with mental health problems in survivors (e.g., depression, PTSD)[3-5]. While (some) more studies have been considering the longitudinal health effects of seismicity, lack of longitudinal design and an unexposed control group have been highlighted as major concerns for studies of natural disasters [3, 5, 6]. Moreover, the impact of natural- cannot be equated with that of induced- seismicity for several reasons: Systematic reviews suggest there is *lower* prevalence of mental health impairment for natural compared to human/technological disasters [7, 8]; but see [9]. Additionally, different stressors are at play: Natural seismicity can be of greater magnitude, causing death and extensive damages to buildings. For induced seismicity, the maximum magnitude of earthquakes tends to be smaller [10, 11]. Risks involve damage to property and an incremental impact on health,

1
2
3 as residents are exposed to long-term stressors (e.g., damages; changing community
4 relations; conflicts of interest with powerful institutions [12, 13]).
5
6

7
8 Factual information regarding the health impact of induced seismicity is sparse.
9
10 Cross-sectional self-report studies [14-16] and an evaluation of health records of
11 exposed adults[17] in the context of unconventional gas extraction, suggest
12 associations between induced seismicity and increased (psychosomatic) health
13 symptoms (e.g., sleep disruption, headaches, stress). It is difficult to draw conclusions
14 regarding the impact of seismicity from such studies: Exposure to (the consequences
15 of) seismicity is not distinguished from other risk factors (e.g., wastewater injections).
16
17 Additionally, most studies lack a non-exposed control group and a reliable baseline, and
18 we know of none that consider the longitudinal effects of exposure.
19
20
21
22
23
24
25
26
27

28
29 This lack of information regarding the (long-term) impact of induced seismicity on
30 health is problematic. The occurrence of induced earthquakes is increasingly common
31 across the globe: 1174 projects worldwide report induced seismicity [18]. High-profile
32 cases of induced earthquakes have occurred in Oklahoma, U.S.A., and (on a smaller
33 scale) Lancashire, UK [19, 20]. There are rising concerns regarding the consequences
34 thereof within exposed populations, coupled with calls to policy makers for monitoring
35 and contingency planning [19]. Policy makers need to weigh the wider economic
36 benefits against potential drawbacks for exposed residents [21].
37
38
39
40
41
42
43
44
45
46

47 The present work was designed to address the lack of information regarding the
48 long-term impact of induced seismicity for residents: It studies the longitudinal
49 (psychosomatic) health impact of induced seismicity on a group exposed to the
50 consequences of seismicity (damage to housing) versus a control group not exposed to
51
52
53
54
55
56
57
58
59
60

1
2
3 these consequences. The study was conducted in the province of Groningen,
4 Netherlands, where conventional gas extraction from the largest gas field in Europe
5 takes place¹. While the magnitude of seismic events (up to 3.6 Richter) is generally
6 considered 'light', their magnitude has increased over the past 30 years, making this a
7 slow-onset disaster, and their impact is felt well beyond the gas field boundaries. The
8 recurrent earthquakes damage housing in a region not prepared for seismic activity [22]
9 and the governmental response to damage compensation has been considered
10 inadequate [23]

11
12 The present study is novel in charting the chronic impact of exposure to damage
13 on health over a time period of almost two years, on a large sample. We tested the
14 following hypotheses: 1. Exposure versus non-exposure will have a negative impact on
15 (psychosomatic) health outcomes. 2. Increases in exposure are related to poorer health
16 outcomes.

17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60

METHOD

Setting and exposure

The study was conducted in the province of Groningen, Netherlands, where conventional gas extraction from the largest gas field in Europe takes place. Exposed residents experience rising concerns about physical safety, loss of property value and uncertainty about the future[23, 24].The benefits of extraction flow to the operator (the

¹ See Figure S1 for more information on seismicity in this province

1
2
3 Netherlands petroleum company, NAM) and the national government, while damage
4 repair and compensation by these entities has been criticized as being inadequate[23].
5
6
7

8 Seismicity has increased over time. While the magnitude of seismic events (up to
9 3.6 Richter) is generally considered 'light', their impact is felt well beyond the gas field
10 boundaries. Also, multiple factors (limited depth & high rates of occurrence of
11 earthquakes; surface constitution) contribute to considerable damage to housing in a
12 region not prepared for seismic activity[22]. For these reasons, documented damage
13 has proven the most proximal measure of exposure, compared to indicators of
14 seismicity[25].
15
16
17
18
19
20
21
22
23
24
25

26 Sample and recruitment

27
28
29 A stratified random sample was drawn of 25000 residents of the province of Groningen,
30 aged 16 and over, from the official municipal population records which is a complete
31 register of all legal residents. Sampling occurred in areas where damage is reported
32 and from outlying areas where this is not the case. Postal-code areas that were rural
33 and strongly affected by damage were oversampled². Residents received letters with
34 personal login codes and one reminder. Eighteen percent (N=4577) signed up for the
35 study, and later received invitations to all questionnaires. Of these 4577, 86% (3934)
36 filled out the first questionnaire. Baseline equivalence of non-exposed and exposed
37 groups was assessed. Differences between groups were significant but small. Those
38 with multiple damage to homes were slightly younger ($r^2 = .014$), more highly educated
39
40
41
42
43
44
45
46
47
48
49
50
51
52

53
54 _____
55 ² In the Netherlands, 4-number postal-code areas provide reasonably accurate geographic positioning,
56 whilst preserving anonymity. Data about damage in each area was provided by the institution handling
57 damage claims, the Centrum voor Veilig Wonen.
58
59
60

1
2
3 (Cramer's $V=.062$), and more likely to be male ($V=.072$). The first two characteristics
4
5 suggest the exposed group might be slightly healthier. We statistically controlled for
6
7 these characteristics.
8
9

10 11 Data sources

12 13 14 15 16 Procedure

17
18
19 Questionnaires were sent via an email link or by post. A reminder was sent after 2
20
21 weeks. Participants (T1: $N=3934$; T5: $N=2150$) completed measures at 5 time points
22
23 during 2 years (T1: February 2016, T2: June 2016; T3: November 2016; T4: April 2017;
24
25 T5: November 2017; see Table 2).
26
27
28
29

30 31 Study Variables

32
33 *Exposure to consequences of gas extraction* was operationalized in two ways. Chronic
34
35 physical exposure to ground motion was assessed by the cumulative peak ground
36
37 acceleration (PGA_{cum}) on the basis of "shakemaps" provided by the Dutch geological
38
39 survey (KNMI)³. Personal exposure to damage due to ground motion was assessed
40
41 every timepoint by asking participants to indicate how often their home had been
42
43 damaged (never, once or multiple times)⁴.
44
45
46
47
48
49
50
51
52

53
54 ³ KNMI calculates shakemaps based on motion sensor readings. For each participant, the PGA of all
55 events modelled by KNMI between 2012 and 2017 was summed, to create an index of exposure to
56 ground motion before and during the study.

57 ⁴ See supplementary materials (table S1) for demographic characteristics by level of damage exposure.
58
59

1
2
3 *Demographic variables* included gender, age and completed education level
4
5 (categorized into ‘low’ (no, elementary, or pre-vocational education), ‘middle’ (secondary
6
7 or vocational education), or ‘high’ (higher education) level of education).
8
9

10 *(Psychosomatic) health outcomes* were assessed at (almost) all time points
11
12 (Table 2) as follows via:
13

14 1. The WHO and Statistics Netherlands recommended validated health survey
15
16 item assessing *self-rated health* [26] (‘how good is your health in general?’, from ‘very
17
18 poor’ to ‘excellent’ on a 5 point scale), which is part of the SF-36 [27].
19
20

21 2. *Stress-related health symptoms* were based on a validated scale of symptoms
22
23 of disaster impact [28]. This list of symptoms was shortened by authors (JB, FG, TP):
24
25 symptoms associated with chronic stress were retained⁵. Consequences of exposure to
26
27 toxic substances and noise (e.g., hearing problems) were deemed irrelevant for
28
29 earthquakes and removed. Ten symptoms (stomach problems, heart palpitations,
30
31 headaches, dizziness/lightheadedness, sensitivity to light/sounds, muscle/joint pains,
32
33 irritability, memory/concentration problems, insomnia, tiredness) were assessed by
34
35 asking ‘how often have you experienced the following complaint(s) in the past four
36
37 weeks’ with response options ‘never, rarely, occasionally, often, most times,
38
39 continuously’. Aggregate health index scores were computed for stress-related health
40
41 symptoms, so that individuals have a score of 0 to 100, with 100 representing optimal
42
43 health. Psychometric properties of the aggregate scale were adequate. Correlations
44
45 among items ranged from ordinal rho 0.26 to 0.72 (median=0.39). A single factor
46
47 explained 46% of variance. Scale reliability was good with omega=.90.
48
49
50
51
52

53
54
55 _____
56 ⁵ Notably, at the level of individuals who suffer these complaints they are referred to as “medically
57
58 unexplained” because they can have multiple sources, among which is chronic stress.
59

1
2
3 3. The five-item validated Mental Health Inventory (MHI-5), part of the Short
4 Form Health Survey (SF-36), measuring general *mental health* [27, 29]. The MHI-5 has
5 a score of 0 to 100. A score of 100 represents optimal mental health.
6
7
8
9

10 11 12 Data management and Analysis 13 14

15 Analyses controlled for age, gender and education level. Analyses were weighted
16 to correct for sampling effects of age, gender and degree of exposure of postal-code
17 areas⁶. The weights were developed to counteract any potential distortive effect due to
18 age composition, among others (e.g., because younger people were underrepresented,
19 see results section). We report the weighted results. The unweighted results were very
20 similar.
21
22
23
24
25
26
27

28
29 To assess the impact of exposure to gas extraction on health over time, we
30 constructed multilevel conditional growth models on the three health indices with
31 damage to housing as the (between group) predictor[30]. Participants with missing data
32 on the health indices were retained, as multilevel modelling is robust to missingness in
33 estimation of model outcomes.
34
35
36
37
38
39

40 Models were tested in a step-wise approach, first including control variables
41 (gender, age, level of education) and time. At the next step, physical exposure (PGA_{cum})
42 was added, followed by earthquake damage at time 1 and the increase of damage since
43 time 1. The final model included the interaction between damage and time. Model fit
44
45
46
47
48
49
50
51
52
53
54

55 ⁶ As mentioned, we oversampled rural areas as well as the most heavily exposed areas. The
56 geographical weighting was added to control for this overrepresentation.
57
58
59
60

1
2
3 was compared to assess which variables best predicted health outcomes. The best
4 fitting models were those including the interaction of damage by time (see Table 3).
5
6

7
8 To highlight the implications of the findings, we distinguished poor and good
9 health on the basis of health scores, enabling us to compute odds ratios (OR) and
10 relative risk. For mental health we used the conventional criterion of MHI < 60 as
11 cutoff[31]. For perceived health we classified “good” and “outstanding” as good health
12 and all other scale points as poor (conform international convention). For symptoms we
13 devised our own cutoff based on distributional characteristics combined with content
14 criteria: A classification of < 60 as poor health resulted in 9% of the unaffected
15 population being classified as such. Odds ratios were calculated in weighted models,
16 controlling for age, education and gender.
17
18
19
20
21
22
23
24
25
26
27
28
29

30 **Public involvement**

31
32 The research setup (design and outcome measures) was discussed with an advisory
33 board consisting of institutions (e.g., local municipalities) and representatives of the
34 public (e.g., action groups). The present work has been disseminated in a public report.
35
36
37
38
39
40

41 **RESULTS**

42 **Sample characteristics**

43
44 There were no significant fluctuations in sample composition over time in terms
45 of gender, education level and damage to own housing (see Table 2). Young
46 respondents were underrepresented. There was attrition during the study. Dropout
47 characteristics revealed no differences between exposed vs. control groups and no
48 association between dropout and health. Analyses showed no indications that attrition
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 influenced any of the effects reported below. Over time, the average age of participants
4 increased, as young people tended to have a higher likelihood of dropout. It is important
5 to note that additional analyses found no significant interaction effect between age and
6 exposure, suggesting that the effects of exposure were age-independent. Because the
7 sample was not entirely representative and attrition relatively high, we carefully checked
8 the potential consequences thereof and found no indications this influenced results.
9

10
11
12
13
14
15
16
17 Regarding levels of exposure, we know from the damage claims register⁷ that the
18 rates of exposure vary substantially within the region: in central areas up to 100% of
19 homes have reported damage at least once. Outside these areas, there is progressively
20 less damage. A substantial part of the province has (nearly) no damage. Average levels
21 of damage are closely associated with ground motion[25]: In postal-code areas where
22 0% damage was reported until January 2016, there was hardly any exposure to ground
23 motion (total ground motion $PGA_{cum}=0.07 \text{ mm/s}^2$). Only 3% of the sample located in this
24 area suspected having damage due to earthquakes. In the areas where up to 20%
25 damage was previously reported, total ground motion was somewhat higher
26 ($PGA_{cum}=0.64 \text{ mm/s}^2$) and more people, 26% of the sample, indicated suspecting they
27 have damage. And in the areas where 20% to 100% had reported damage, ground
28 motion was considerably higher, $PGA_{cum}=4.13 \text{ mm/s}^2$ and high percentage of our
29 sample, 83%, suspected having damage.
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

47 **The impact of exposure to gas extraction on health over time**

48
49
50
51
52
53
54

55
56 ⁷ Provided by the institution handling damage claims, the Centrum voor Veilig Wonen
57
58
59
60

1
2
3 The analyses of conditional growth models on self-rated health, stress-related health
4 problems and mental health showed consistent results across all three indicators. Table
5
6
7
8 3 shows the final results for all variables.
9

10 Important to note is that, after including control variables in step 1, there was a
11
12 significant effect of exposure to physical ground motion (PGA_{cum}) on all three health
13
14 indicators: more ground motion was associated with poorer health. The effect of time
15
16 was also significant: over time, health deteriorated.
17
18

19 In step 2, we included damage to housing. Having damage once had no
20
21 significant effect on any of the health indicators. Only participants with multiple damages
22
23 experienced negative health consequences.
24
25

26 The effects of ground motion were suppressed by the larger effects of exposure
27
28 to multiple damage on all health indicators ($p's < .01$). The suppression occurs because
29
30 damage and total ground motion are strongly correlated. It does not mean that the
31
32 association between exposure to ground motion and health should be disregarded:
33
34 There might, for example, be some health effects of "peak exposure" to strong ground
35
36 motion in the weeks or months after an earthquake. The current analysis does not
37
38 address such peak exposure effects because it only assesses average impact on health
39
40 over the entire two-year period and gradual changes in health over time.
41
42
43

44 In step 3, the significant 'multiple damage (vs no damage) X time' interaction
45
46 reveals that exposure to multiple damages is associated with a deterioration of health
47
48 over time. The inclusion of this interaction variable improved model fit.
49
50

51 To interpret these effects of exposure to damage and assess their magnitude, we
52
53 calculated odds ratios for health measures at every time point, as well as the average
54
55
56
57
58
59
60

1
2
3 impact of exposure over time (Table 4). Inhabitants exposed to damage once are only
4 marginally (and not significantly) affected compared with a no-damage control group
5
6 (averaged odds ratios range from 1.10 to 1.20). Those exposed to damage multiple
7
8 times are more likely to report poor self-rated health (OR = 1.64, with a 95% confidence
9
10 interval of 1.31;2.04), more stress-related health symptoms (OR = 2.52 [1.89;3.38]) and
11
12 less good mental health (OR = 1.83 [1.40;2.39]) than those without damage. This
13
14 indicates that damage has a considerable impact on participants' health⁸.
15
16
17
18

19 The table also suggests that differences between groups increase over time.
20
21 Odds ratios for the difference between those with multiple damage and no damage are
22
23 considerably higher 21 months after first measurement for self-rated health (OR = 2.00
24
25 [1.57;2.55]), mental health (OR = 2.38 [1.78;3.21]) and stress related health symptoms
26
27 (OR = 3.36 [2.45;4.68]). In terms of relative risk, this means that those whose homes
28
29 have multiple damage at T5 are 1.60[1.37;1.86] times more likely to report poor health,
30
31 2.11 [1.63;2.74] times more likely to report negative mental health and 2.84 [2.14;3.76]
32
33 times more at risk of elevated levels of stress related health symptoms.
34
35
36
37

38 We also compared the weighted means of the ORs of control variables that are
39
40 known correlates of health (age, gender, level of education) to the effect of damage
41
42 (Figure 1). Across the three health measures, effect sizes (ORs) of damage are slightly
43
44 larger than those of education (for a high versus low level of education, the average
45
46 odds ratios over time are .53 [.41;.68] for self-rated health; OR = .58 [.42;.81] for mental
47
48 health; and OR = .56 [.41;.79] for stress-related health symptoms).
49
50
51
52
53
54

55 ⁸ We also investigated whether women's health is affected differently by this stressor than men's, but as
56 evidenced in Table S2 in the supplementary materials, this is not the case.
57
58
59
60

DISCUSSION

Natural and induced seismicity can have negative consequences for local populations due to (acute or accumulated) health threats and irreversible changes to the living environment. Yet, so far studies have not assessed the accumulated impact of (the consequences of) induced seismicity on (psychosomatic) health *over time*.

Moreover, most studies lack a non-exposure control group. The present study aimed to address these shortcomings by studying the impact of exposure to gas extraction (and subsequent damage to housing), compared to a no-exposure control group, on health over a time period of 21 months. Our study provides strong indications that exposure to negative side-effects of induced seismicity (e.g., damage to people's homes) constitutes an increasing health risk over time: We found that those who self-reported having multiple damages to housing experienced more negative health consequences than those without damage. Moreover, these effects increased over time. Results showed that chronic physical exposure to ground motion (assessed objectively) was also related to health, although less strongly than reporting multiple personal damages .

To our knowledge, this is the only study of the long-term impact of induced seismicity on health. Therefore, we can only compare our results with the long-term impacts of very different types of disaster - limiting comparability. For one, the Chernobyl nuclear disaster: Study participants lived in a seriously contaminated area approximately 50 miles from Chernobyl. 6.5 years post disaster, inhabitants were twice as likely to have negative self-rated health (OR:2.25[1.96-2.58]) and psychological distress (OR:1.93[1.69-2.22]), compared to a non-exposed control group[32].

Chernobyl clearly constitutes a very different type of disaster and health risk (radiation

1
2
3 exposure). The Brisbane floods were also very different in many respects (e.g., sudden
4 disaster onset; deaths) but with some comparable outcomes, such as considerable
5 damage to homes. 6-7 months post-disaster, those exposed to flooding were twice as
6 likely to report psychological distress compared to the non-exposed[33]. It appears that
7 the health impact of these very different and in many ways more 'acute' disasters are, in
8 terms of effect size, somewhat comparable to the health impact of the more chronic
9 exposure to induced earthquakes caused by gas extraction. One potential reason for
10 the comparable effect sizes, is that our study focused not just on the environmental
11 effect (e.g., amount of total ground motion) but zoomed in on the subgroup who were
12 severely affected because they had multiple instances of damage to their own home.
13
14 We further speculate that the man-made nature of the hazard (the fact that earthquakes
15 are induced) may also enhance the impact on the population.
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30

31 The present work also provides first time insights into the development of
32 (psychosomatic) health symptoms in response to chronic disaster. In the area of acute
33 disaster response, studies on longitudinal health impact reveal that distress decreases
34 over time[34, 35], implying recovery of victims. Yet looking at discussions comparing
35 chronic man-made (technological) disasters to acute natural disasters, we see the
36 present context shares elements identified as reasons for potential long-term health
37 impact of technological disasters: A strong element of culpability in causing disaster,
38 concerns about damage compensation after disaster and uncertainty regarding when
39 disaster impact will end ("the book is never closed"; p.148, [12]; [36-38]. In line with this
40 work, our findings suggest that for chronic disasters/hazards, negative effects can
41 accumulate over time, presumably because the recurrent threat and poor crisis
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 response leads to an accumulation of stress.
4

5 **Limitations**

6
7 A potential limitation of this sample could be concerns about its
8 representativeness: For one, attrition was 45.3% over time and younger respondents
9 were somewhat underrepresented. However, attrition was no different for the exposed
10 and non-exposed groups, was unrelated to health outcomes, and all further analyses
11 suggest that neither attrition nor sample characteristics had any substantial influence on
12 results and conclusions drawn. Secondly, there might be an influence of confounding
13 variables. Yet we believe effect sizes are robust: 1. The exposed and control groups
14 were very similar regarding key population and geographical characteristics 2. Follow-
15 up analyses revealed no interactions between any of the population characteristics and
16 the effects of exposure.
17
18
19
20
21
22
23
24
25
26
27
28
29

30
31 Thirdly, responses could have been biased because participants knew the survey
32 was about the social impact of gas extraction. It is relevant here that an 'objective'
33 exposure measure (peak ground acceleration) revealed comparable health outcomes to
34 self-reported exposure. Moreover, analyses on a cross-sectional representative sample
35 of residents (N=16340) in the 2016 health monitor of Statistics Netherlands, the National
36 Institute for Public Health and public health services found comparable results. In this
37 survey, the study intent was not clear.
38
39
40
41
42
43
44
45

46
47 One of the three health measures included, stress-related health symptoms, was
48 an adaptation of a previously validated symptoms list[39], shortened for this specific
49 study. Although the shortened version was not previously validated, it was
50 psychometrically sound. Also, patterns are comparable across health measures, two of
51
52
53
54
55
56
57
58
59
60

1
2
3 which are validated.
4

5 One of our exposure measures is self-reported damage. It is possible that
6 damage is perceived differently depending on people's health status. Importantly,
7 physical exposure to ground motion was associated with significant health effects. But
8 effects of damage were stronger. This could be because damage is a more precise and
9 proximate indicator of how individuals are affected by exposure, but also because of
10 recursive effects of (mental) health on perceived damage. But
11 effects of damage were stronger. This could be because damage is a more precise and
12 proximate indicator of how individuals are affected by exposure, but also because of
13 recursive effects of (mental) health on perceived damage.
14
15
16
17
18

19 An important issue is generalizability: Is the situation in Groningen comparable to
20 other areas with induced seismicity (e.g., fracking, wastewater injections)? We can only
21 make reasoned inferences. Induced earthquakes are relatively common in energy
22 projects which involve injection[40]. A priori, similar health consequences could occur in
23 all sites in which populations are affected by induced earthquakes. Moreover, the
24 vulnerability of people exposed to seismicity is likely influenced by similar factors:
25 negative consequences are man-made and involve safety, health and social risks [12,
26 13]. In sum, although more research on the impact of induced seismicity is needed [41],
27 we suggest effects are likely to generalize beyond the Groningen case.
28
29
30
31
32
33
34
35
36
37
38
39

40 **Practical implications**

41
42 The consequences of induced seismicity pose challenges to decision-makers.
43 Benefits to the public good need to be balanced against the welfare of local populations
44 [21]. As projects involving induced seismicity rapidly grow, governments and businesses
45 face decisions whether to invest and how to manage risks. Our work provides a case
46 study of what occurs if seismicity is not kept in check. It can increase awareness of the
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 vulnerability of exposed populations and provide important input for future decision
4
5 making, monitoring and contingency planning.
6

7 **Conclusion**

8
9
10 Recent years have seen a rise in induced seismicity. Little is known about the
11
12 (longitudinal) impact thereof on (psychosomatic) health. The present study is the first to
13
14 our knowledge evidencing the long-term impact of induced seismicity on health.
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 **Funding:** This study was funded by the National Coordinator Groningen. Award/grant
4 number: not applicable.
5

6
7 **Contributorship:** KS, BK, JR, JB, FO, FG and TP contributed to the research
8 questions and study design. JR and FO contributed to data collection. BK and TP
9 conducted statistical analyses. KS, BK and TP interpreted the results and wrote the
10 initial draft of the manuscript. All authors commented on the final draft of the manuscript.
11 BK and TP had full access to the data in the study and can take responsibility for the
12 integrity of the data and the accuracy of the data analysis.
13
14

15 **Conflict of Interest:** The authors declare that they have no conflict of interest.
16

17 **Ethical approval:** All procedures performed in studies involving human participants
18 were in accordance with the ethical standards of the ethical board of the department of
19 psychology of the University of Groningen, The Netherlands (research code ppo-015-
20 085).
21

22 **Informed consent:** Informed consent was obtained from all individual participants
23 included in the study.
24

25 **Data sharing statement:** Data collected for this study are not available in order to
26 guarantee anonymity of participants.
27
28
29
30
31
32

Table 1.
List of definitions

Conventional gas extraction	Extraction through drilling in deep subsoil reservoirs without the injection of chemical liquids.
Fracking	A stimulation technique in which a rock is fractured by a pressured liquid in order to extract oil or gas from wells.
Induced seismicity	Seismic events that are a result of human activity.
Natural seismicity	Seismic events that have a natural cause (e.g., volcanic eruption).
Peak ground acceleration	Measure of the maximum increase in ground motion during an earthquake, recorded by a ground motion sensor.
Psychosomatic health	Health outcomes involving both mind and body.
Richter scale	Measure of strength of earthquakes with a logarithmic scale.
Shale gas	A natural gas that is trapped in fine grained sediment in rock.
Unconventional gas extraction	Gas reservoirs that require a special stimulation technique to extract gas (e.g., by injecting large quantities of fluids underground).

Table 2

Demographic characteristics of participants participating in separate measurements: total number of participants participating in that measurement, decline of number of participants participating as compared to the number of participants participating at T1, mean age, distribution of level of education, distribution of personal exposure to damage due to gas extraction, distribution of gender, and amount of participants that completed the three health measures in that measurement. Netherlands 2016-2017

	T1	T2	T3	T4	T5
	Feb '16	June '16	Nov '16	Apr '17	Nov '17
Total N	3934	3153	2638	2351	2150
Attrition (compared to T1)	-	19.9%	32.9%	40.2%	45.3%
Age (mean)	56.54	57.74	57.72	58.90	59.98
Level of education (N)					
Low	968 (24.6%)	772 (24.5%)	616 (23.4%)	589 (25.1%)	535 (24.9%)
Middle	1252 (31.8%)	970 (30.8%)	815 (30.9%)	713 (30.3%)	639 (29.7%)
High	1533 (39.0%)	1238 (39.3%)	1068 (40.5%)	944 (40.2%)	852 (39.6%)
Gender (N)					
Male	1967 (50.0%)	1547 (49.1%)	1306 (49.5%)	1182 (50.3%)	1068 (49.7%)
Female	1849 (47.0%)	1480 (46.9%)	1231 (46.7%)	1097 (46.7%)	990 (46.0%)
Exposure to damage (N)					
None	1477 (37.5%)	1204 (38.2%)	1027 (38.9%)	910 (38.7%)	846 (39.3%)
One time	913 (23.2%)	626 (19.9%)	554 (21.0%)	505 (21.5%)	459 (21.3%)
Multiple	1057 (26.9%)	1055 (33.5%)	940 (35.6%)	775 (33.0%)	736 (34.2%)
Perceived health (N)	3821 (97.1%)	-	2540 (96.3%)	2206 (93.8%)	2059 (95.8%)
Stress related health symptoms (N)	3767 (95.8%)	-	2533 (96.0%)	2206 (93.8%)	2045 (95.1%)
Mental health (N)	3711 (94.3%)	2819 (89.4%)	2501 (94.8%)	2179 (92.7%)	2021 (94.0%)

Table 3

Results of multilevel conditional growth models: *Unstandardized parameter estimates and standard errors for the association between time, damage, and the interaction between time and damage on perceived health, stress-related health symptoms, and mental health – adjusted for gender, age, level of education and ground motion (cumulative PGA). Netherlands 2016-2017.*

	Perceived health	Stress-related health symptoms ¹	Mental health
Gender	-0.05* (0.02)	-5.40*** (0.49)	-2.68*** (0.46)
Age	-0.01*** (0.001)	-0.02 (0.02)	0.07*** (0.02)
Level of education (middle)	0.08* (0.03)	0.61 (0.67)	1.01 (0.62)
Level of education (high)	0.24*** (0.03)	3.02*** (0.63)	2.94*** (0.59)
Cumulative PGA	-0.001 (0.004)	0.03 (0.09)	-0.01 (0.08)
Time	-0.01 (0.01)	-0.25* (0.13)	-0.49*** (0.15)
Damage (one time)	-0.01 (0.03)	-0.46 (0.75)	-0.27 (0.63)
Damage (multiple)	-0.12*** (0.03)	-4.31*** (0.76)	-3.35*** (0.65)
Time * Damage (one time)	-0.02 (0.01)	-0.13 (0.20)	-0.07 (0.24)
Time * Damage (multiple)	-0.03*** (0.01)	-0.45* (0.19)	-0.60** (0.23)
Constant	3.86*** (0.03)	80.19*** (0.67)	77.78*** (0.60)
Observations	10,256	9,100	9,686
Log Likelihood	-10,104.58	-36,205.01	-38,020.51
Akaike Inf. Crit.	20,239.16	72,440.02	76,071.02
Bayesian Inf. Crit.	20,347.69	72,546.76	76,178.69

Note. *p<0.05; **p<0.01; ***p<0.001

1. Stress-related health symptoms were reverse-coded such that higher levels indicate less stress

Table 4

Proportion of participants who have poor health and OR of participants who have poor health with damage (compared to those with no damage) across measurements, with 95% confidence intervals – adjusted for age, gender and level of education.

Netherlands 2016-2017

Measurement	Damage	Percentage poor health	Odds ratio
Self-rated health			
T1	None	22.2% [19.9%;24.5%]	-
	One time	22.5% [19.6%;25.4%]	1.02 [0.82;1.26]
	Multiple	25.6% [22.7%;28.4%]	1.21 [0.99;1.47]
T3	None	21.6% [18.8%;24.3%]	-
	One time	24.4% [20.5%;28.3%]	1.17 [0.90;1.53]
	Multiple	32.4% [29.2%;35.7%]	1.75 [1.41;2.18]
T4	None	21.3% [18.4%;24.2%]	-
	One time	30.0% [25.7%;34.4%]	1.60 [1.22;2.09]
	Multiple	35.5% [31.8%;39.2%]	2.06 [1.63;2.61]
T5	None	23.6% [20.3%;26.9%]	-
	One time	27.5% [22.9%;32.1%]	1.23 [0.92;1.65]
	Multiple	38.0% [34.0%;42.0%]	2.00 [1.57;2.55]
Weighted average	None	22.1% [19.4%;24.9%]	-
	One time	25.6% [21.8%;29.4%]	1.20 [0.93;1.55]
	Multiple	31.8% [28.5%;35.2%]	1.64 [1.31;2.04]
Symptoms			
T1	None	9.2% [7.7%;10.8%]	-
	One time	10.0% [7.9%;12.1%]	1.09 [0.81;1.47]
	Multiple	17.3% [14.9%;19.7%]	2.08 [1.62;2.68]
T3	None	7.1% [5.5%;8.8%]	-
	One time	6.5% [4.3%;8.6%]	0.90 [0.58;1.37]
	Multiple	13.7% [11.4%;16.1%]	2.09 [1.55;2.85]
T4	None	8.1% [6.2%;10.0%]	-
	One time	9.4% [6.7%;12.1%]	1.18 [0.78;1.75]
	Multiple	21.8% [18.7%;25.0%]	3.24 [2.40;4.42]
T5	None	7.1% [5.3%;9.0%]	-
	One time	9.1% [6.3%;11.9%]	1.30 [0.84;1.99]
	Multiple	20.3% [17.0%;23.5%]	3.36 [2.45;4.68]
Weighted average	None	8.0% [6.4%;9.8%]	-
	One time	8.8% [6.5%;11.2%]	1.10 [0.75;1.60]
	Multiple	18.0% [15.3%;20.7%]	2.52 [1.89;3.38]
Mental health			

T1	None	8.5% [7.0%;10.0%]	-
	One time	9.0% [7.0%;10.9%]	1.06 [0.78;1.43]
	Multiple	12.4% [10.3%;14.5%]	1.53 [1.18;1.98]
T2	None	8.5% [6.8%;10.2%]	-
	One time	9.2% [6.9%;11.6%]	1.09 [0.77;1.54]
	Multiple	18.1% [15.6%;20.7%]	2.40 [1.86;3.13]
T3	None	11.1% [9.0%;13.2%]	-
	One time	12.0% [9.2%;14.9%]	1.10 [0.79;1.51]
	Multiple	14.5% [12.1%;16.9%]	1.36 [1.04;1.77]
T4	None	11.9% [9.6%;14.1%]	-
	One time	11.8% [8.9%;14.7%]	0.99 [0.71;1.38]
	Multiple	20.3% [17.2%;23.4%]	1.9 [1.46;2.47]
T5	None	9.0% [6.9%;11.1%]	-
	One time	12.5% [9.3%;15.7%]	1.44 [0.99;2.07]
	Multiple	19.1% [15.9%;22.2%]	2.38 [1.78;3.21]
Weighted average	None	9.7% [7.8%;11.5%]	-
	One time	10.6% [8.1%;13.2%]	1.11 [0.80;1.55]
	Multiple	16.4% [13.8%;19.0%]	1.83 [1.40;2.39]

Note. Scores were categorised as low health as follows: 1) very poor, poor, or fair perceived health; 2) a score below 60 for stress related health symptoms, and 3) a score below 60 for mental health.

REFERENCES

- 1 Konkel L. In the Neighborhood of 18 Million: Estimating How Many People Live Near Oil and Gas Wells, *Environ Health Perspect* 2017;125:UNSP 124003 doi:10.1289/EHP2553 [published Online First: DEC].
- 2 U.S. Energy Information Administration. United States Shale gas reserves per state. 2017;2019.
- 3 Dai W, Chen L, Lai Z, et al. The incidence of post-traumatic stress disorder among survivors after earthquakes: A systematic review and meta-analysis, *BMC Psychiatry* 2016;16.
- 4 Neria Y, Nandi A, Galea S. Post-traumatic stress disorder following disasters: A systematic review, *Psychol Med* 2008;38:467-80 doi:10.1017/S0033291707001353.
- 5 Beaglehole B, Mulder RT, Frampton CM, et al. Psychological distress and psychiatric disorder after natural disasters: systematic review and meta-analysis, *The British Journal of Psychiatry* 2018;213:716-22.
- 6 Goldmann E, Galea S. Mental health consequences of disasters, *Annu Rev Public Health* 2014;35:169-83.
- 7 Galea S, Nandi A, Vlahov D. The epidemiology of post-traumatic stress disorder after disasters, *Epidemiol Rev* 2005;27:78-91.
- 8 Norris FH, Friedman MJ, Watson PJ. 60,000 disaster victims speak: Part II. Summary and implications of the disaster mental health research, *Psychiatry: Interpersonal and biological processes* 2002;65:240-60.
- 9 Rubonis AV, Bickman L. Psychological impairment in the wake of disaster: The disaster–psychopathology relationship. *Psychol Bull* 1991;109:384.
- 10 Keranen KM, Weingarten M. Induced Seismicity, *Annual Review of Earth and Planetary Sciences, Vol 46* 2018;46:149-74 doi:10.1146/annurev-earth-082517-010054.
- 11 van der Elst, Nicholas J., Page MT, Weiser DA, et al. Induced earthquake magnitudes are as large as (statistically) expected, *Journal of Geophysical Research-Solid Earth* 2016;121:4575-90 doi:10.1002/2016JB012818 [published

- 1
2
3 Online First: JUN].
4
5 12 Couch SR, Kroll-Smith JS. The chronic technical disaster: Toward a social scientific
6 perspective, *Social Science Quarterly* 1985;66:564.
7
8 13 Sangaramoorthy T, Jamison AM, Boyle MD, et al. Place-based perceptions of the
9 impacts of fracking along the Marcellus Shale, *Soc Sci Med* 2016;151:27-37.
10
11 14 Rabinowitz PM, Slizovskiy IB, Lamers V, et al. Proximity to Natural Gas Wells and
12 Reported Health Status: Results of a Household Survey in Washington County,
13 Pennsylvania, *Environ Health Perspect* 2015;123:21-6 doi:10.1289/ehp.1307732.
14
15 15 Steinzor N, Subra W, Sumi L. Investigating links between shale gas development
16 and health impacts through a community survey project in Pennsylvania. *New
17 solutions : a journal of environmental and occupational health policy : NS*
18 2013;23:55-83 doi:10.2190/NS.23.1.e.
19
20 16 Tustin AW, Hirsch AG, Rasmussen SG, et al. Associations between Unconventional
21 Natural Gas Development and Nasal and Sinus, Migraine Headache, and
22 Fatigue Symptoms in Pennsylvania, *Environ Health Perspect* 2017;125:189-97
23 doi:10.1289/EHP281.
24
25 17 Weinberger B, Greiner LH, Walleigh L, et al. Health symptoms in residents living
26 near shale gas activity: A retrospective record review from the Environmental
27 Health Project. *Preventive medicine reports* 2017;8:112-5
28 doi:10.1016/j.pmedr.2017.09.002.
29
30 18 Wilson MP, Foulger GR, Gluyas JG, et al. HiQuake: The human-induced earthquake
31 database, *Seismol Res Lett* 2017;88:1560-5.
32
33 19 Aczel MR, Makuch KE. Shale, Quakes, and High Stakes: Regulating Fracking-
34 Induced Seismicity in Oklahoma, USA and Lancashire, UK, *Case Studies in the
35 Environment* 2019.
36
37 20 Keranen KM, Weingarten M, Abers GA, et al. Sharp increase in central Oklahoma
38 seismicity since 2008 induced by massive wastewater injection, *Science*
39 2014;345:448-51 doi:10.1126/science.1255802 [published Online First: JUL 25].
40
41 21 Fleming RC, Reins L. Shale gas extraction, precaution and prevention: A
42 conversation on regulatory responses, *Energy Research & Social Science*
43 2016;20:131-41 doi:10.1016/j.erss.2016.05.013 [published Online First: OCT].
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3 22 Vlek C. Rise and reduction of induced earthquakes in the Groningen gas field, 1991-
4 2018: statistical trends, social impacts, and policy change, *Environ Earth Sci*
5 2019;78:59 doi:10.1007/s12665-019-8051-4 [published Online First: FEB].
6
7
8 23 Dutch Safety Board. Earthquake risks in Groningen. Research concerning the role
9 population safety played in decision making procedures about gas extraction
10 (1959-2014) , 2015.
11
12
13 24 Postmes T, Stroebe K, Richardson J, et al. Consequences of ground motion for the
14 Groningen population: Experienced safety, health and future perspective 2016-
15 2017. *University of Groningen* 2018.
16
17
18 25 Geurts C, Steenbergen R. Note for the Dutch State Supervision of Mines: The
19 relation between Peak Ground Acceleration and the risk of damage for induced
20 earthquakes in Groningen. *The Netherlands Organisation for Applied Scientific*
21 *Research* 2016.
22
23
24 26 Pappas G. Health interview surveys: Towards international harmonization of
25 methods and instruments - deBruin,A, Picavet,HSJ, Nossikoy,A, *Soc Sci Med*
26 1997;44:1431-2 doi:10.1016/S0277-9536(97)84078-6 [published Online First:
27 MAY].
28
29
30 27 Ware JE, Gandek B, IQOLA Project. Overview of the SF-36 Health Survey and the
31 International Quality of Life Assessment (IQOLA) Project, *J Clin Epidemiol*
32 1998;51:903-12 doi:10.1016/S0895-4356(98)00081-X [published Online First:
33 NOV].
34
35
36 28 Van den Berg B, Yzermans CJ, Van der Velden, Peter G., et al. Risk Factors for
37 Unexplained Symptoms After a Disaster: A Five-Year Longitudinal Study in
38 General Practice, *Psychosomatics* 2009;50:69-77 doi:10.1176/appi.psy.50.1.69.
39
40
41 29 Berwick DM, Murphy JM, Goldman PA, et al. Performance of a five-item mental
42 health screening test. *Med Care* 1991.
43
44
45 30 Raudenbush SW, Bryk AS. Hierarchical linear models: Applications and data
46 analysis methods: Sage 2002.
47
48
49 31 Rumpf H, Meyer C, Hapke U, et al. Screening for mental health: validity of the MHI-5
50 using DSM-IV Axis I psychiatric disorders as gold standard, *Psychiatry Res*
51 2001;105:243-53.
52
53
54
55
56
57
58
59
60

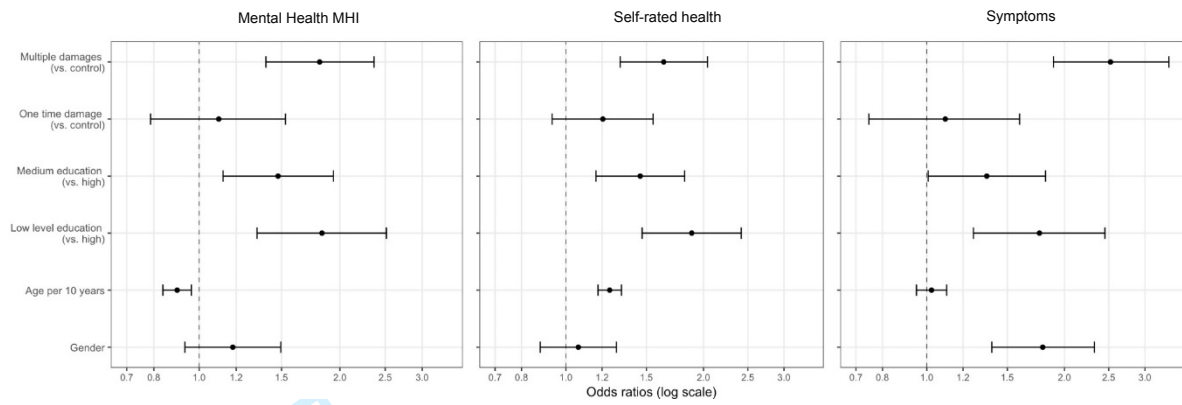
- 1
2
3 32 Havenaar J, Rumyantzeva G, Kasyanenko A, et al. Health effects of the Chernobyl
4 disaster: Illness or illness behavior? A comparative general health survey in two
5 former Soviet regions, *Environ Health Perspect* 1997;105:1533-7
6
7 doi:10.2307/3433666 [published Online First: DEC].
8
9
10 33 Alderman K, Turner LR, Tong S. Assessment of the Health Impacts of the 2011
11 Summer Floods in Brisbane, *Dis Med Public Health Prep* 2013;7:380-6
12
13 doi:10.1017/dmp.2013.42 [published Online First: AUG].
14
15 34 Lowell A, Suarez-Jimenez B, Helpman L, et al. 9/11-related PTSD among highly
16 exposed populations: a systematic review 15 years after the attack, *Psychol Med*
17
18 2018;48:537-53 doi:10.1017/S0033291717002033 [published Online First: MAR].
19
20 35 van der Velden, Peter G., Wong A, Boshuizen HC, et al. Persistent mental health
21 disturbances during the 10years after a disaster: Four-wave longitudinal
22 comparative study, *Psychiatry Clin Neurosci* 2013;67:110-8
23
24 doi:10.1111/pcn.12022 [published Online First: FEB].
25
26
27 36 Baum A. Implications of psychological research on stress and technological
28 accidents. *Am Psychol* 1993;48:665.
29
30 37 Picou JS. The “talking circle” as sociological practice: Cultural transformation of
31 chronic disaster impacts, *Sociological Practice* 2000;2:77-97.
32
33 38 Picou JS, Marshall BK, Gill DA. Disaster, litigation, and the corrosive community,
34
35 *Social forces* 2004;82:1493-522.
36
37 39 van den Berg B, Grievink L, Yzermans J, et al. Medically unexplained physical
38 symptoms in the aftermath of disasters, *Epidemiol Rev* 2005;27:92-106
39
40 doi:10.1093/epirev/mxi001.
41
42 40 Ellsworth WL. Injection-induced earthquakes, *Science* 2013;341:1225942.
43
44 41 Hirsch JK, Smalley KB, Selby-Nelson EM, et al. Psychosocial Impact of Fracking: a
45
46 Review of the Literature on the Mental Health Consequences of Hydraulic
47 Fracturing, *International Journal of Mental Health and Addiction* 2018;16:1-15
48
49 doi:10.1007/s11469-017-9792-5 [published Online First: FEB].
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Figure 1. Weighted average odds ratios.

For peer review only

Figure 1. Weighted average odds ratios.

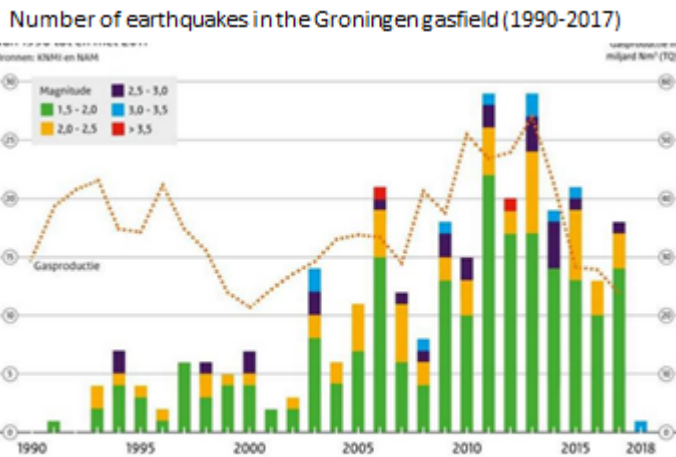


For peer review only

Supplementary materials

Seismicity in the Groningen gasfield

Figure S1: Number of earthquakes and volume of gas production in the Groningen gasfield:



The volume of gas production in the subsoil of Groningen is presented as a dotted line in Figure 2. The number of earthquakes magnitude 2 or higher increased from 2003 onwards. The earthquake of August 2012 in the village of Huizinge (magnitude 3,6 on Richter scale) was a landmark event that caused unrest and great concern among the population in the province of Groningen. It was the heaviest earthquake measured in the province. The magnitude of earthquakes is recorded by the Dutch national borehole network, the regional accelerometer network and all additional seismic stations in the south of the Netherlands. European seismic stations reported the event at epicentral distances up to 800 km (Dost and Kraaiipoel, 2012).

410,000 residents of the province of Groningen are exposed to these induced earthquakes: they live in a postcode area where damage has been recognized by the oil company responsible (NAM, a joint venture of Shell and Exxon). Of these, 134,363 adults report having damage to their property (Postmes et al., 2017). Of these 68,343 report having damage multiple times.

Looking worldwide, there are 1174 locations in which induced seismicity is taking place. 11% of seismicity is due to conventional oil or gas extraction (see inducedearthquakes.org/)

References

Dost B and Kraaiipoel D. The August 16, 2012 earthquake near Huizinge in Groningen province. Royal Dutch Meteorological Institute, 2013.

Postmes, T., Stroebe, K., Richardson, J., LeKander, B., Oldersma, F., Broer, J. & Greven, F. (2018). Gevolgen van bodembeweging voor Groningers: Ervaren veiligheid, gezondheid en toekomstperspectief 2016-2017. Groningen: Heymans Instituut, Rijksuniversiteit Groningen.

Table S1

Demographic characteristics of participants completing separate measurements per level of damage: total sample size, mean age, distribution of level of education, distribution of level of damage, distribution of gender, and amount of participants that completed the health measures. Netherlands 2016-2017

Damage to house at T1		T1 Feb '16	T2 June '16	T3 Nov '16	T4 Apr '17	T5 Nov '17	
None	Total N	1477	1166	968	886	801	
	Age (mean)	57.67	59.13	59.13	60.28	61.48	
	Level of education (N)	Low	430	340	266	267	238
		Middle	460	351	290	255	226
		High	562	453	396	349	324
	Gender (N)	Male	794	621	515	471	427
		Female	683	545	453	415	374
	Perceived health (N)	1467	-	934	835	784	
	Stress related health symptoms (N)	1452	-	937	836	780	
Mental health (N)	1432	1048	920	828	769		
One time	Total N	913	730	608	559	490	
	Age (mean)	58.32	58.87	58.81	60.06	60.86	
	Level of education (N)	Low	237	191	155	143	131
		Middle	295	235	195	182	159
		High	363	295	250	227	193
	Gender (N)	Male	505	398	345	323	279
		Female	407	332	263	236	211
	Perceived health (N)	907	-	587	521	464	
	Stress related health symptoms (N)	894	-	584	522	463	
Mental health (N)	895	666	581	517	456		
Multiple	Total N	1057	825	704	609	558	
	Age (M)	54.06	55.57	55.60	56.71	57.70	
	Level of education (N)	Low	215	168	133	120	110
		Middle	381	289	246	213	188
		High	445	356	315	268	253
	Gender (N)	Male	493	385	323	284	269
		Female	563	440	381	325	289
	Perceived health (N)	1048	-	683	578	537	
	Stress related health symptoms (N)	1041	-	675	577	530	
Mental health (N)	1018	739	674	570	528		

Table S2

Unstandardized regression parameter estimates and standard errors for the association between time, damage, and the interaction between time and damage on perceived health, stress-related health symptoms, and mental health, and the interaction between gender and damage on perceived health, stress-related health symptoms, and mental health – adjusted for gender, age, level of education and ground motion (cumulative PGA). Netherlands 2016-2017.

	Perceived health	Stress-related health symptoms ¹	Mental health
Gender	-0.07 (0.04)	-5.08*** (0.75)	-2.81*** (0.70)
Age	-0.01*** (0.001)	-0.02 (0.02)	0.07*** (0.02)
Level of education (middle)	0.08* (0.03)	0.62 (0.67)	0.99 (0.62)
Level of education (high)	0.23*** (0.03)	3.03*** (0.63)	2.92*** (0.59)
Cumulative PGA	-0.001 (0.004)	0.03 (0.09)	-0.01 (0.08)
Time	-0.01 (0.01)	-0.25* (0.13)	-0.49*** (0.15)
Damage (one time)	-0.02 (0.04)	-0.19 (0.93)	-0.05 (0.81)
Damage (multiple)	-0.14** (0.04)	-4.04*** (0.95)	-3.79*** (0.84)
Time * Damage (one time)	-0.02 (0.01)	-0.13 (0.20)	-0.07 (0.24)
Time * Damage (multiple)	-0.03*** (0.01)	-0.45* (0.19)	-0.60** (0.23)
Gender * Damage (one time)	0.03 (0.06)	-0.58 (1.21)	-0.51 (1.13)
Gender * Damage (multiple)	0.04 (0.05)	-0.55 (1.15)	0.85 (1.07)
Constant	3.87*** (0.03)	80.04*** (0.73)	77.86*** (0.65)
Observations	10,256	9,100	9,686
Log Likelihood	-10,104.34	-36,204.85	-38,019.84
Akaike Inf. Crit.	20,242.68	72,443.70	76,073.68
Bayesian Inf. Crit.	20,365.69	72,564.67	76,195.71

Note. * p<0.05; ** p<0.01; *** p<0.001

1. Stress-related health symptoms were reverse-coded such that higher levels indicate less stress

STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No.	Recommendation	Page No.	Relevant text from manuscript
Title and abstract	1	(a) Indicate the study's design with a commonly used term in the title or the abstract	1/2	Title is mentioned on page 1
		(b) Provide in the abstract an informative and balanced summary of what was done and what was found	2	
Introduction				
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	4/5	
Objectives	3	State specific objectives, including any prespecified hypotheses	5/6	The present work was designed to address the lack of information regarding the long-term impact of induced seismicity for residents: It studies the longitudinal (psychosomatic) health impact of induced seismicity on a group exposed to the consequences of seismicity (damage to housing) versus a control group not exposed to these consequences." "The present study is novel in charting the chronic impact of exposure to damage on health over a time period of almost two years, on a large sample. We tested the following hypotheses: 1. Exposure versus

non-exposure will have a negative impact on (psychosomatic) health outcomes. 2. Increases in exposure are related to poorer health outcomes.”

Methods

Study design	4	Present key elements of study design early in the paper	5-8	
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	6-8	<p>“A stratified random sample was drawn of 25000 residents of the province of Groningen, aged 16 and over, from the official municipal population records which is a complete register of all legal residents. Sampling occurred in areas where damage is reported and from outlying areas where this is not the case. Postal-code areas that were rural and strongly affected by damage were oversampled . Residents received letters with personal login codes and one reminder. Eighteen percent (N=4577) signed up for the study, and later received invitations to all questionnaires. Of these 4577, 86% (3934) filled out the first questionnaire.”;</p> <p>“Questionnaires were sent via</p>

				an email link or by post. A reminder was sent after 2 weeks. Participants (T1: N=3934; T5: N=2150) completed measures at 5 time points during 2 years (T1: February 2016, T2: June 2016; T3: November 2016; T4: April 2017; T5: November 2017; see Table 2).
Participants	6	<p>(a) <i>Cohort study</i>—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up</p> <p><i>Case-control study</i>—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls</p> <p><i>Cross-sectional study</i>—Give the eligibility criteria, and the sources and methods of selection of participants</p>	7	
		<p>(b) <i>Cohort study</i>—For matched studies, give matching criteria and number of exposed and unexposed</p> <p><i>Case-control study</i>—For matched studies, give matching criteria and the number of controls per case</p>		
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	8-10	
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	8-10	
Bias	9	Describe any efforts to address potential sources of bias	10	Analyses controlled for age, gender and education level. Analyses were weighted to correct for sampling effects of age, gender and degree of exposure of postal-code areas . The weights were developed to

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

counteract any potential
distortive effect due to age
composition, among others
(e.g., because younger people
were underrepresented, see
results section). We report the
weighted results. The
unweighted results were very
similar.

Study size	10	Explain how the study size was arrived at	7
------------	----	---	---

Continued on next page

For peer review only

1				
2	Quantitative	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which	10-11
3	variables		groupings were chosen and why	
4				
5	Statistical	12	(a) Describe all statistical methods, including those used to control for confounding	10-11
6	methods		(b) Describe any methods used to examine subgroups and interactions	10-11
7			(c) Explain how missing data were addressed	10
8				Participants with missing data on
9				the health indices were retained, as
10				multilevel modelling is robust to
11				missingness in estimation of model
12				outcomes. See Table 2 for an
13				overview of the number of
14				participants completing each health
15				measure per time point.
16			(d) <i>Cohort study</i> —If applicable, explain how loss to follow-up was addressed	11-12
17			<i>Case-control study</i> —If applicable, explain how matching of cases and controls was addressed	
18			<i>Cross-sectional study</i> —If applicable, describe analytical methods taking account of sampling	
19			strategy	
20				There was attrition during the
21				study. Dropout characteristics
22				revealed no differences between
23				exposed vs. control groups and no
24				association between dropout and
25				health. Analyses showed no
26				indications that attrition influenced
27				any of the effects reported below.
28				Over time, the average age of
29				participants increased, as young
30				people tended to have a higher
31				likelihood of dropout. It is
32				important to note that additional
33				analyses found no significant
34				interaction effect between age and
35				exposure, suggesting that the
36				effects of exposure were age-
37				independent. Because the sample
38				was not entirely representative and
39				attrition relatively high, we
40				carefully checked the potential
41				consequences thereof and found no
42				indications this influenced results.
43			(e) Describe any sensitivity analyses	

Results

Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed		Table 2
		(b) Give reasons for non-participation at each stage	N/A	
		(c) Consider use of a flow diagram	N/A	
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders		Table 2
		(b) Indicate number of participants with missing data for each variable of interest	N/A	
		(c) <i>Cohort study</i> —Summarise follow-up time (eg, average and total amount)		
Outcome data	15*	<i>Cohort study</i> —Report numbers of outcome events or summary measures over time		
		<i>Case-control study</i> —Report numbers in each exposure category, or summary measures of exposure		
		<i>Cross-sectional study</i> —Report numbers of outcome events or summary measures		
Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	13-14	Table 3/4
		(b) Report category boundaries when continuous variables were categorized	11	Tables 3/4
		(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period		

Continued on next page

Other analyses	1	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	
	7		
Discussion			
Key results	1	Summarise key results with reference to study objectives	15
	8		
Limitations	1	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss	16-17
	9	both direction and magnitude of any potential bias	
Interpretation	2	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of	16
	0	analyses, results from similar studies, and other relevant evidence	
Generalisability	2	Discuss the generalisability (external validity) of the study results	17-18
	1		
Other information			
Funding	2	Give the source of funding and the role of the funders for the present study and, if applicable, for the	19
	2	original study on which the present article is based	

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at <http://www.plosmedicine.org/>, Annals of Internal Medicine at <http://www.annals.org/>, and Epidemiology at <http://www.epidem.com/>). Information on the STROBE Initiative is available at www.strobe-statement.org.