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The effect of evidence and theory-based health advice accompanying smartphone air quality alerts on adherence to preventative recommendations during poor air quality days: A randomised controlled trial

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A R T I C L E   I N F O
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A B S T R A C T

Although poor air quality can have a negative impact on human health, studies have shown suboptimal levels of adherence to health advice associated with air quality alerts. The present study compared the behavioural impact of the UK Air Quality Index (DAQI) with an alternative message format, using a 2 (general population vs. at-risk individuals) X 2 (usual DAQI messages vs. behaviourally enhanced messages) factorial design. Messages were sent via a smartphone application. Eighty-two participants were randomly allocated to the experimental groups. It was found that the enhanced messages (targeting messages specificity and psychosocial predictors of behaviour change) increased intentions to make permanent behavioural changes to reduce exposure, compared to the control group (V = 0.23). This effect was mediated by a reduced perception of not having enough time to follow the health advice received (b = −0.769, BCa CI [−2.588, 0.533]). It was also found that higher worry about air pollution, perceived severity, perceived efficacy of the recommended behaviour and self-efficacy were predictive of self-reported behaviour change at four weeks. In response to a real moderate air quality alert, among those with a pre-existing lung condition, more respondents in the intervention group reported to have used their preventer inhaler compared to the control group (V = 0.49).

On the other hand, the two message formats performed similarly when intentions were collected in relation to a hypothetical high air pollution scenario, with all groups showing relatively high intentions to change behaviours. This study expands the currently limited understanding of how to improve the behavioural impact of existing air quality alerts.

1. Background

According to estimates from the World Health Organisation released in 2014, in 2012 around 3.7 million people died prematurely in the world as a result of exposure to ambient air pollution (World Health Organization (WHO), 2014). Findings from epidemiological and toxicological research have highlighted the negative effects of short- and long-term exposure to air pollution on both premature mortality and morbidity from cardiopulmonary disease (for an overview, see (Kelly and Fussell, 2015)). A recent study conducted in London found that single day exposure to traffic-related pollutants was associated with increased hospitalisations for adult cardiovascular and paediatric respiratory problems (Samoli et al., 2016). In the UK, monitoring networks measure the levels of different air pollutants and these measurements are usually provided by the Department for Environment, Food & Rural Affairs (DEFRA) in the form of daily air quality indices.

Abbreviations: KCL, King’s College London; NIHR HPRU, National Institute of Health Research, Health Protection Research Unit; PHE, Public Health England; DEFRA, Department for Environment, Food & Rural Affairs; DAQI, Daily Air Quality Index; COM-B, Capability, Opportunity, Motivation – Behaviour Model

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components. However, evidence suggests that the traditional strategy of simply informing people about high pollution episodes may not be effective (Johnson, 2012). A recently published systematic review (D’Antoni et al., 2017) aimed to understand to what extent air quality information influences protective behaviours in the general public, and to identify the psychosocial factors associated with adherence and non-adherence to health advice received through air quality information services. The review (D’Antoni et al., 2017) not only found suboptimal adherence levels but also identified several facilitators and barriers to adherence. Some of the facilitators included beliefs that air pollution can have negative health effects (i.e. perceived severity), outcome expectancies (e.g., beliefs that something can be done to reduce smog), beliefs about the health benefits of DAQI adoption (i.e. response efficacy), and receiving advice from health care professionals. Barriers to adherence included: lack of understanding of the indices, being exposed to health messages that failed to increase both concern about air pollution and perceived susceptibility, as well as perceived lack of self-efficacy/locus of control, reliance on sensory cues and lack of time to make behavioural changes.

The systematic review concluded that to improve the behavioural impact of existing air quality alerts, these should target the psychosocial factors identified in their review.

In addition, evidence shows the importance of developing messages that target specificity, which refers to the extent to which a message provides a detailed description of the recommended behaviour (O’Keefe, 2016). A meta-analysis of 18 studies (O’Keefe, 1997) found that messages providing health recommendations with a more specific description seem to be significantly more persuasive than generic recommendations ($r = 0.10, k = 18, N = 11,105$). For instance, Frantz found that adding procedurally explicit precautions for safe use of products (e.g. ‘Open windows to vent vapours to outdoors’ or ‘Wear rubber gloves and protective glasses’) increased adherence to recommendations on how to use these products, compared to more generic instructions (e.g. ‘Use in a well-ventilated area’ or ‘Avoid contact with eyes and skin’) (Frantz, 1994). It is plausible that more specific descriptions of recommended behaviours make it easier for the targeted audience to imagine themselves performing that action, which in turn enhances persuasiveness (O’Keefe, 1997). Moreover, as a person imagines themselves performing a specific action, their perceived ability to engage with that specific behaviour (i.e. self-efficacy) might be enhanced, and in turn this would increase actual adherence (O’Keefe, 1997).

The purpose of the present study was to test whether theory and evidence-based alternative communication formats, targeting message specificity and previously identified psychosocial predictors of adherence, could improve the behavioural impact of an existing alert system delivered by smartphone, compared to the official messages sent in association with the UK DAQIs. To capture the factors associated with behaviour change, we decided to use the COM-B model (Michie et al., 2011), which is currently considered one of the most comprehensive models to explain adherence (Jackson et al., 2014). The model assumes that three key components ‘capability’ (e.g. knowledge about a health threat and physical and psychological capabilities), ‘opportunity’ (e.g. access to resources and social influence), and ‘motivation’ (e.g. beliefs about a health threat and relative treatment, emotions, and habits) can affect ‘behaviour’. According to this framework, for behaviour to change it is necessary to influence one or more of these components.

### 1.1. Research questions

**Primary questions:**

1) What is the main effect of using behaviourally enhanced messages, compared to the currently used DAQI messages, to present the health advice associated with air quality notifications for a hypothetical high air pollution scenario on adherence intentions?

Prediction:

A) The behaviourally enhanced messages will lead to stronger intentions to adhere to recommendations.

2) What is the main effect of using a behaviourally enhanced message, compared to the currently used DAQI messages, to present the health advice associated with air quality notifications on actual behaviour changes at four weeks?

Prediction:

A) The enhanced messages will lead to greater behaviour changes.

3) In case of a real alert being issued during the study period, how do the different messages affect actual behaviour change?

Prediction:

A) The enhanced messages will lead to greater behaviour change.

**Secondary questions:**

4) If there is a format effect, which variables mediate the relationship between the information format and behaviour change?

5) Which factors are associated with greater behaviour change across all groups?

### 2. Methods

#### 2.1. Design

This was a randomised control trial using a 2-way factorial design, with target population (2 levels: general population vs. individuals with a pre-existing health condition) and message format (2 levels: usual message format vs. behaviourally enhanced messages) as between-factors. Participants were randomised to either the usual message group or the enhanced message.

#### 2.2. Improving the behavioural impact of air quality alerts

##### 2.2.1. Targeted psychosocial predictors

The control groups received usual air quality alerts and health advice based on the UK DAQI messages, whilst the intervention groups received behaviourally enhanced health messages designed to specifically target those psychosocial factors affecting adherence to health advice as highlighted in previous studies (D’Antoni et al., 2017). Using the COM-B model, the factors targeted can be categorised as part of the Psychological Capability component of the model (i.e. knowledge about the health impact of exposure to air pollution), and as part of the Motivation component (i.e. perceived severity of air pollution, perceived susceptibility, perceived efficacy of protective behaviours, self-efficacy, perceived negative consequences associated with protective behaviours, reliance on sensory cue, and action planning) (See Appendix A). In addition, study participants who reported having a respiratory condition and who were randomly allocated in the intervention group, also received specific additional messages targeting beliefs about the
efficacy and side effects of inhalers, and medication self-efficacy. These were based on previous studies identifying specific illness and medication beliefs associated with non-adherence to preventer medications in asthmatic patients (Horne and Weinman, 2002; Petrie et al., 2012).

2.2.2. Targeting message specificity

In the current study, at-risk individuals and generally healthy participants were randomly allocated to receive health advice in a different message format. Participants in the control group received the usual UK DAQI message format containing less specific recommendations (e.g. advice for at-risk individuals in case of high air pollution: ‘Adults and children with lung problems, and adults with heart problems, should reduce strenuous physical exertion, particularly outdoors’). On the other hand, the intervention group received more specific recommendations (‘Adults and children with lung problems, adults with heart problems, and older people, should reduce levels and length of physical activity outdoors. Where possible, change: travel route or exercise location (e.g. use our app to find less polluted roads or parks) or time (e.g. mornings or less polluted times’)). Moreover, one of the messages targeting self-efficacy contained instructions on what to do (i.e. ‘People who are able to move outdoor physical activities to the mornings or side roads can protect themselves from air pollution. Start by making one change to your next scheduled activity (e.g. start by walking as far from the kerb as possible) and build up from there’). It is worth noting that the messages had to be fairly short as they were sent via a smartphone application.

Control and intervention groups were compared in intended and actual involvement in the study (Fig. 1).

2.2.3. CityAir smartphone application

This is an application designed and developed by the City of London Corporation and King’s College London (KCL). The CityAir app version 2.0.4 (available at: https://www.cityoflondon.gov.uk/business/environmental-health/environmental-protection/air-quality/Pages/New-CityAir-App.aspx) is currently available for iOS and Android and is compatible with iPhone, iPad and iPod touch and Android devices. This application allows users to sign up for air pollution alerts and find less polluted routes when levels of air pollution are high in London.

For the purpose of the current study, we launched an alternative app version, which allowed the researchers to send different types of messages for the control and intervention groups during the study period. To increase message relevance, targeted advice was sent to people with lung and/or heart or other existing condition, and the generally healthy public (Appendix A). It is worth noting that the current UK DAQI does not provide targeted advice for people with heart conditions apart from reducing exertion, and the main advice for people with lung conditions is to consider using their reliever inhaler more often. Usually CityAir sends alerts for moderate, high and very high air pollution to users in the at-risk group and sends alerts for high and very high air pollution only to users in the other groups. However, for the purpose of the current study, the alternative version of the application also sent moderate alerts and associated advice to the general population group. This was to test the UK DAQI advice in case of a real moderate air pollution episode during the study period. Personal device IDs (i.e. an anonymous and unique identifier attributed to an individual mobile device) were used to link questionnaires completed at different time points by the same study participant. At the end of the study, a new version of CityAir was issued to allow the application to revert to its usual functions.

2.2.4. Participants

Eligible participants had to be members of the general public in the adult age range (> 18 years), be fluent in English, working or living in Greater London (as this is the geographical area that CityAir covers), and being new or existing users of the City Air smartphone application. Existing users were informed about the study through a notification sent via CityAir (http://cityairapp.com/), whilst new users were informed about the study via adverts sent in KCL email circulars, via Facebook, Twitter, and an advert on the LondonAir website (https://www.londonair.org.uk/LondonAir/Default.aspx).

Sample size was calculated using the G*Power statistical power analysis (Faul et al., 2009), to give 80% power to detect a statistically significant difference in the main outcome measures at α = 0.05, if a small to medium effect size of f = 0.02 or higher is observed (Johnson, 2003), adjusting for one covariate. Given the possibility of dropout, we inflated the sample size by 20%, and aimed to achieve a minimum sample size of n = 240.

2.2.5. Study procedure

Recruitment started on 23rd July and was closed on 3rd August 2017. Data collection was completed on 8th September 2017. Once they had confirmed their eligibility and opted to take part in the study, participants were redirected to a survey, using an online platform (https://www.surveymonkey.co.uk/). Respondents completed the questionnaires on their phone (using mobile friendly surveys powered by SurveyMonkey®), in their own time (see Appendix C). Participants were asked to indicate whether they had a pre-existing health condition. Based on their answers, they were divided into two groups (general public and at-risk respondents).

Respondents in both groups were randomised via an algorithm run by CityAir to either a control or intervention group. See participants’ involvement in the study (Fig. 1).

Participants were then asked to read the scenario of a hypothetical high pollution episode and asked to indicate their intentions to follow the health advice given (i.e. baseline adherence intentions). After completion of the first questionnaire, all participants were able to receive real-time CityAir notifications about real air pollution episodes (notifications of poor air quality were sent the day before, with a reminder and relevant health advice sent on the following morning at 6 am). Whilst the control group was set to receive air quality notifications and associated health advice in the usual UK DAQI format, the intervention group was set to receive health advice in an enhanced format (see Materials section).

We wanted to test if a proposed change in the wording of the health advice associated with air quality alerts had any effect on respondents’ intended and actual behaviour change in response to this information. Because we did not want to bias participants, we did not tell them how the wording had been changed. In addition, for three weeks (between 5 and 6 pm) people in the intervention arm received additional health messages targeting specific psychosocial factors affecting adherence. The additional messages received by the intervention/at-risk group were slightly adjusted to be more relevant to the specific health condition they reported (e.g. respiratory, heart or other condition) (see Fig. 2 and Appendix A).

A moderate air quality alert and related health advice was sent on the 28th of August due to a real episode of air pollution. On this occasion, participants in all groups were asked to complete a short questionnaire assessing their actual behaviour change in response to the alert received. Participants who did not complete this questionnaire, received a reminder the following day. At the end of the study (at four weeks) respondents were asked to complete one final questionnaire. Participants who completed the last questionnaire were entered into a prize draw for 1 of 40 £50.00 gift vouchers.

2.2.6. Statistical analyses

To produce more reliable results all the analyses were performed
using 1000 bootstraps.

ANCOVAs (analysis of covariance) were performed for behavioural intentions in relation to the high air pollution hypothetical scenario and actual behaviour change at four weeks, adjusting for baseline data collected about one month earlier (target population and intervention/control group were entered as fixed factors). A two-way MANOVA (multivariate analysis of variance) tested differences between health and intervention groups in stopping physical exercise due to receiving air quality alerts, and emergency department access. Sidak corrections were used to adjust for multiple analyses. Chi square tests were performed to analyse differences in proportion of self-reported actual behaviour change between groups, in relation to a real moderate air pollution episode. ‘Unsure’ answers in relation to actual behaviour change were treated as system missing and excluded from analyses. Multiple linear regressions were used to assess the associations between main predictor variables and self-reported behaviour change at four weeks. Mediation effects of predictor variables on significant behavioural changes were tested using PROCESS macro (Hayes, 2013).

2.2.7. Materials

Table 1 shows the health advice accompanying air quality alerts in both the usual and enhanced version (i.e. targeting message specificity). Appendix A shows the additional messages sent to the intervention group and targeting specific psychosocial factors. Readability scores were calculated for all messages (using a readability tool available at: https://www.webpagefx.com/tools/read-able/) and reported in Table 1 and Appendix A. To reduce the likelihood of confounding effects, the behaviourally enhanced messages have a similar word count and identical readability scores of 8 (i.e. they should be easily understood by someone 13 to 14 years old). All research materials and questionnaires were tested through Patient and Public Involvement (PPI) workshops (See Appendix B).

2.2.8. Questionnaires

Appendix D reports a summary of the items included in the questionnaires used.

3. Results

Between 23rd July and 3rd August 2017 (i.e. when the version 2.0.2 of CityAir was launched for the current study), we recorded 6310 automatic or manual upgrades for iOS devices, and 439 for Android.
devices. This data refers to each device upgrade and not to each users’ upgrade, as users may have downloaded the application onto different devices (e.g. phones and tablets). Unfortunately, CityAir did not record the exact number of users who visualised the notification about the study through its homepage and how many refused participation. Therefore, it is only possible to calculate an approximate response rate of 3.53%. This was an acceptable response, considering that 238 initial questionnaires were submitted to SurveyMonkey, which was in line
| Level of pollution | UK DAQI messages | Behaviourally enhanced messages (targeting message specificity) |
|-------------------|------------------|--------------------------------------------------|
| General public    | Enjoy your activities as usual. | Enjoy your activities as usual. However, if you expected to experience a high level of pollution, you can reduce levels and length of physical activity. |
| At-risk           | Enjoy your activities as usual. | Enjoy your activities as usual. However, if you expected to experience a high level of pollution, you can reduce levels and length of physical activity. |

**Moderate (4–6)**
- Enjoy your activities as usual.
- You can also consider changing your route or mode of transportation.
- Travel route or mode of transportation (e.g., use public transport or choose less polluted roads).
- Exercise location (use apps to find less polluted roads or parks).

**High (7–9)**
- Enjoy your activities as usual.
- However, if you want to stay indoors, you can reduce levels and length of physical activity.
- Time (e.g., mornings or less polluted times).
- Exercise location (use our app to find less polluted roads or parks).

**Very high (10)**
- Reduce physical exertion, particularly outdoors.
- People with asthma may find they need to use their reliever inhaler more often.
- Where possible, change:
  - Travel route or
  - Exercise location (e.g., use our app to find less polluted roads or parks)
  - Time (e.g., mornings or less polluted times).

Note: For each message, word count and readability score are reported (i.e., higher scores indicate more complex sentences).
with our power calculation (i.e. estimation of 240 responses, including 20% inflation). Of the submitted questionnaires, 13 (5.5%) were incomplete, leaving a total of 225 complete initial questionnaires.

At four weeks, 101 final questionnaires were submitted. Of these questionnaires, 9 were removed as incomplete, 8 could not be matched to any initial questionnaire, and 2 were removed as the participants reported in the comments to have not received any alert or information. Therefore, only 82 cases (i.e. participants who completed both the first and last questionnaire) were considered for subsequent analyses, with an attrition rate of 64% (See Appendix E). We believe that this attrition rate might be at least partially explained by a technical problem which occurred in the application at the end of week 3, and caused some users to receive multiple empty notifications for 24 h. According to data available to CityAir between 3rd August and the 2nd September 2017, 89 Android devices uninstalled the application, no data is available on this for iOS. It is plausible that at least part of these uninstalls were due to this problem.

As a form of sensitivity analysis, we checked for distribution of baseline sample characteristics (including age group, gender, qualification, employment, ethnicity) in the initial sample ($n = 225$ completing the first questionnaire) and the final sample used ($n = 82$ completing both initial and final questionnaire). As expected, in the initial sample there were no statistically significant differences between groups in the baseline characteristics. However, as might have been expected, people in the at-risk group ($M = 45.9$ yrs.) were older than in groups in the baseline characteristics. Apart from mean age in the at-risk group ($M = 48.3$ yrs.), no statistically significant differences between groups in any of the baseline characteristics were found. However, as might have been expected, people in the at-risk group ($M = 45.9$ yrs.) were older than in the general public group ($M = 37.5$ yrs.).

### 3.1. Primary outcomes

**Hypothesis 1(A).** The enhanced format will lead to stronger intentions to adhere to recommendations associated with the hypothetical high air pollution scenario: was not supported by the data. No significant differences between the health and intervention groups, nor interaction effects were found.

Overall, respondents revealed low intentions to use their preventer inhaler, with no significant differences between groups in the control group ($M = 6.47$, SE = 1.13; 95% CI [3.99, 8.95]) and intervention group ($M = 6.35$, SE = 1.23; 95% CI [4.01, 8.71]).

**Hypothesis 2(A).** The enhanced format will lead to greater behaviour change and action planning at four weeks: was partially supported. Although ninety-one responses were submitted to SurveyMonkey in response to receiving a real moderate air quality alert, only 63 responses could be used for subsequent analyses (See Table 4).

**Hypothesis 3(A).** The enhanced format will lead to greater actual behaviour change in response to a real moderate air pollution alert: was partially supported.
Appendix E for details). This subgroup had a mean age of 41.1 years (SD = 13.3, MIN = 22, MAX = 68), with 58.7% of male respondents. First of all, 61.4% correctly recalled the alert band. Fisher’s exact tests revealed that only a minority of respondents in the control and intervention groups changed their behaviours in response to receiving a real air quality alert about a moderate air pollution episode, with no statistically significant differences between groups in any of the recorded behavioural outcomes (see Table 4).

However, in relation to respondents with a pre-existing lung condition (n = 16: six in the control group and 10 in the intervention group), a likelihood ratio test revealed a statistically significant difference between intervention and control groups in the use of the preventative inhaler, $\chi^2(1) = 4.020, p = 0.045$, Cramer’s V = 0.492. In particular, among those who used their preventative inhaler, 77.8% (n = 7) were in the intervention group and 22.2% (n = 2) in the control group. To make sure that our sample characteristics were comparable with national statistics about people with asthma in the UK, we accessed data from the British Lung Foundation (British Lung Foundation, 2016). According to this report, 50.8% of people diagnosed with a lung disease in 2013 were female, which is comparable to our sample of 50% female respondents with respiratory problems. In addition, broadly in line with data from the 2011 General Lifestyle Survey (GLF) (Office for National Statistics, 2013), prevalence of respiratory conditions in our sample was higher in the age group 45–64 years (i.e. 50% in our sample vs. 45 per 1000 people reporting a respiratory condition in the GLF) compared to the younger age group (i.e. 45.8% in our sample vs. 45 per 1000 people in the GLF).

No statistically significant differences were found in carrying the reliever inhaler, as the majority in both groups (100% in the intervention group (n = 9/9), and 71.4% (n = 5/7) in the control group) remembered to carry it with them in response to the alert, $\chi^2(1) = 2.939, p = 0.175$.

### 3.2. Secondary outcomes

Research question 4 (Which variable mediate the relationship between the information format and behaviour change?): To understand which variable mediated the effect of the intervention on considering permanent behavioural changes (see research question 2), we ran a mediation analysis using model 4 of PROCESS Macro (Hayes, 2013). The analysis showed a significant indirect effect of the intervention on the outcome measured through perception of time, $b = −0.769$, BCa CI [−2.588, 0.533]. The direct effect of the intervention was also significant, $b = 2.256$, 95% CI [0.516, 3.997], $Z = 2.54, p = 0.0111$ (See Fig. 4).

Research question 5 (Which factors are associated with greater behaviour change?): Table 5 shows the results of the multiple regression, with forced entry model (robust 1000 bootstraps), which aimed at identifying the predictors of self-reported overall actual behaviour change as measured at four weeks. It was found that higher worry about air pollution, perceived severity of its health consequences, perceived efficacy of the recommended behaviour and self-efficacy were predictive of self-reported behaviour change. The model explained 48% of the variance in adherence.

### 4. Discussion

The present study aimed to investigate whether the systematic manipulation of key communication variables used in health messages provided in association with existing air quality alerts was able to maximise their behavioural impact. Study participants were randomly allocated to either receiving the usual UK DAQI health advice (control...
Table 4
Descriptive statistics for behaviour changes at four weeks, and actual adherence to the real air pollution forecast in the different groups.

| Outcome | General population | At-risk individuals | Control group | Intervention |
|---------|---------------------|---------------------|---------------|--------------|
|         | M (SD; 95% CI) or n (%) | M (SD; 95% CI) or n (%) | M (SD; 95% CI) or n (%) | M (SD; 95% CI) or n (%) |
| Control | Intervention | F or χ² | Df | Sig. | F or χ² | Df | Sig. | η² or V | F or χ² | Df | Sig. | η² or V |
| In the past 4 weeks, how often have you taken action to reduce exposure as recommended? | 3.67 (0.44) 2.68–4.65 | 3.38–5.10 | 0.586 1 0.448 0.011 | 4.29 (0.97) 2.19–6.36 | 3.65 (0.74) 2.21–5.36 | 0.165 1 0.693 0.016 | 3.98 (0.54) 2.82–5.10 | 3.95 (0.44) 3.06–4.94 | 0.002 1 0.964 < 0.001 |
| In the past 4 weeks, have you stopped exercising due to receiving alerts? | 3.18 (0.36) 2.46–3.84 | 3.51 (0.36) 2.83–4.19 | 0.502 1 0.481 0.008 | 3.79 (0.99) 2.41–5.17 | 3.47 (0.79) 2.17–5.79 | 0.365 1 0.554 0.022 | 3.35 (0.35) 2.68–4.09 | 3.70 (0.35) 2.99–4.39 | 0.661 1 0.419 0.008 |
| How physically active were you last week? | 3.65 (0.74) 2.21–5.36 | 2.82–5.10 | 0.661 1 0.419 0.008 |
| In response to a real moderate air pollution forecast (27/08/2017; N = 63) | 3.67 (0.44) 2.68–4.65 | 3.38–5.10 | 0.586 1 0.448 0.011 | 4.29 (0.97) 2.19–6.36 | 3.65 (0.74) 2.21–5.36 | 0.165 1 0.693 0.016 | 3.98 (0.54) 2.82–5.10 | 3.95 (0.44) 3.06–4.94 | 0.002 1 0.964 < 0.001 |
| Behavioural changes and planning at four weeks (N = 82) | In the past 4 weeks, how often have you taken action to reduce exposure as recommended? | 3.67 (0.44) 2.68–4.65 | 3.38–5.10 | 0.586 1 0.448 0.011 | 4.29 (0.97) 2.19–6.36 | 3.65 (0.74) 2.21–5.36 | 0.165 1 0.693 0.016 | 3.98 (0.54) 2.82–5.10 | 3.95 (0.44) 3.06–4.94 | 0.002 1 0.964 < 0.001 |
| In the past 4 weeks, have you stopped exercising due to receiving alerts? | 3.18 (0.36) 2.46–3.84 | 3.51 (0.36) 2.83–4.19 | 0.502 1 0.481 0.008 | 3.79 (0.99) 2.41–5.17 | 3.47 (0.79) 2.17–5.79 | 0.365 1 0.554 0.022 | 3.35 (0.35) 2.68–4.09 | 3.70 (0.35) 2.99–4.39 | 0.661 1 0.419 0.008 |
| How physically active were you last week? | 3.65 (0.74) 2.21–5.36 | 2.82–5.10 | 0.661 1 0.419 0.008 |
| Notes: For the first part of the results, the reported values correspond to the estimated marginal means, after controlling for baseline measurements, and standard errors (SEs) (all analyses use 1000 bootstraps). Frequencies and percentages are reported for actual adherence measured on the 28th of August 2017. Statistically significant differences with a p-value < 0.05 are indicated in bold. Analyses of the variance were performed for the actual behaviour change at 4 weeks (with the intervention/control group entered as fixed factor). These analyses were also run in the subgroups of healthy and at-risk participants: F values, degrees of freedom (Df), p values and eta squared values (η²) are reported. Where chi square tests were performed to analyse differences in proportion of self-reported actual behaviour change between groups the table reports chi square values (χ²) degrees of freedom (Df), p values and Cramer’s V values. |
| Measures: from 1 Not at all to 9 all of the time (answers ‘N/A, I am not aware of any forecast’ were excluded from analyses) |
| Covariates are evaluated at the value = 2.79. |
| Covariates are evaluated at the value = 3.68. |
| Measured from 1 = strongly disagree to 9 = strongly agree, comparisons between groups were performed using a MANOVA. |
| Possible answers: from 1 = not at all, to 7 ≥ 150 min; Covariates are evaluated at the value = 5.78. |
| ‘unsure’ answers were treated as system missing, and excluded from analyses. |
| N = 62 used (1 system missing). |
| N = 59 used (4 system missing). |
| N = 61 used. |
group) or an alternative behaviourally targeted message format (intervention group). The latter included health advice characterised by higher message specificity and sent in conjunction with additional messages targeting specific psychosocial factors found to be associated with higher adherence.

4.1. Intentions to adhere to advice associated with a hypothetical high air pollution scenario

Our findings showed that the message format did not seem to have an impact on adherence intentions for the hypothetical high air pollution scenario, as respondents in both control and intervention groups reported relatively high intentions to follow the advice received. However, it is worth considering that initial high intentions do not necessarily translate into future behaviour (Webb and Sheeran, 2006).

Our study also showed that respondents in the control group were more willing to wear a mask (which is not a behaviour recommended by the UK DAQI), compared to the intervention group. Recent evidence suggests that many commercially available masks do not provide adequate protection (Cherrie et al., 2018). A plausible explanation for these results may be related to the fact that the advice associated with the UK DAQI has little message specificity compared to the more detailed recommendations provided in the intervention group (which clearly identified appropriate behaviours). This vagueness of recommendation might have led to the intention to adopt behaviours based on participants’ personal beliefs rather than the health advice received. The implications of this may be really important depending on what type of not advised behaviour individuals adopt. Future studies should test the advantages of adopting highly specific messages.

4.2. Behaviour changes at 4 weeks

At four weeks, more respondents in the intervention group were reported to have considered making permanent changes to their daily travel route, exercise location or exercise time compared to the control group. A mediation analysis showed that the variable that mediated this effect was perception of having enough time to follow the health advice received, which was positively affected by the intervention.

Fig. 3. Proportion of respondents in the control (n = 13, 32%) and intervention groups (n = 21, 55%) who considered making permanent changes in their daily travel route and/or exercise time or location. See Table 4.

Fig. 4. Mediation analysis (model 4) showing the mediating effect of perception of time on considering permanent behavioural changes. Multiple mediation model of the intervention (intervention vs. control) on the outcome measure. This model aims to identify and explain the processes that underlie an observed relationship between an independent variable and a dependent variable through the inclusion of several hypothetical mediator variables (in this case, worry, perceived susceptibility, perceived severity, perceived efficacy of the advice, self-efficacy, perception of not having time to follow the advice, belief that taking side roads will make the journey longer, and message credibility).

Effect size measures for indirect effects are not available for models with dichotomous outcomes. The coefficients reported represent the direct effect, the effect of the independent variable on each mediator (i.e., a paths) and the effect of each mediator on the dependent variable (b paths) and are standardised. The values reported in the results section correspond to the indirect effect (i.e., a path * b path). All analyses have used 1000 bootstraps.

Significant indirect effects are represented in bold. Baseline measurements were included in the model as covariate and experimental groups coded as a dummy variable (Control = 0; Intervention = 1).

*p = 0.0059; **p = 0.0132; ***p = 0.0111; ****p = 0.0113.
particular, specific additional messages sent to the intervention group targeted beliefs about negative consequences associated with the recommended behaviour (i.e. response costs) such as: ‘The CityAir App can help you find side street routes, which do not necessarily add to your total travel time, and may give you a more pleasant journey’. Messages like this might have led to the observed effect on perception of time, however it is also plausible that the cumulative effect of the other additional messages may explain these results. For instance, other messages targeting action planning (e.g. ‘start by making one change to your next planned activity – e.g. start by walking as far from the kerb as possible and build up from there’) might have helped the participants in the intervention group to imagine themselves performing the recommended behaviour and therefore finding it easier to imagine themselves performing that action (O’Keefe, 1997).

4.3. Behaviour changes during a real-life moderate air pollution episode

During the study period only one real-life episode of moderate air pollution occurred. It was found that only a minority of respondents in the control and intervention groups changed their behaviours, with no statistically significant differences between groups. Healthy participants in both control and intervention groups were mainly advised to enjoy their activities as usual (although participants in the intervention group were also receiving some suggestions of behavioural changes to consider), and therefore no large behaviour changes were expected. On the other hand, among those with a pre-existing lung condition more respondents in the intervention group were reported to have used their preventer inhaler compared to the control group. Considering that past research has highlighted the problem of non-adherence to the preventer inhalers in asthma patients (see (Horne and Weinman, 2002; Petrie et al., 2012)), the potential implications of our findings are important (although they should be taken with caution, given the small sample size). In our study, participants with respiratory problems in the intervention group received specific additional messages targeting beliefs about the severity and susceptibility to air pollution, as well as beliefs about medication response efficacy, response costs, and self-efficacy. Our findings support those of Petrie and colleagues (Petrie et al., 2012) who sent tailored messages to asthma patients, based on their illness and treatment beliefs, and found improved adherence to their preventer inhaler in the intervention group compared to a control group, not receiving the tailored messages. Unfortunately, in our study we were unable to identify exactly which variable mediated the intervention effect on use of preventer inhaler as data on relevant variables was missing for 25% of this sub-sample.

4.4. Predictors of behaviour change at 4 weeks

It was found that higher worry about air pollution, perceived severity of its health consequences, perceived efficacy of the recommended behaviour and self-efficacy were predictive of higher frequency of behaviour change at four weeks. The model explained 48% of the variance in adherence. All these factors can be ascribed to the Reflective Motivation component of the COM-B model (Michie et al., 2011). These results are in line with previous systematic reviews investigating factors impacting health advice uptake in relation to air quality alerts (D’Antoni et al., 2017). It is worth noting that several researchers (e.g. (Miller et al., 2012; Lin and Bautista, 2016)) have emphasised that fear or worry generating approaches alone may not be effective, and that a more appropriate approach should also include a promotion of higher perception of efficacy, through providing specific advice on how to manage the health risk presented.

4.5. Strengths

A strength of the present study is that it expands the literature about the behavioural impact of air quality alerts and the factors affecting intentions and actual behaviours. The messages tested in the present study were developed in line with previous literature. To the best of our knowledge, this was the first study comparing the official UK DAQI health advice with enhanced messages. This is important as it has been highlighted that governmental agencies often fail to evaluate their own messages, and that environmental agency-developed messages have in some circumstances obtained the opposite effect of the one wanted (see (Johnson, 2003)).

4.6. Limitations

The current study has several limitations. The sample used was at least partially composed of a convenience sample of existing users of a smartphone application which sends air quality alerts in London. Therefore, it is plausible that these people were particularly aware of the problem of air pollution and that, in particular those accepting to remain in the study for the whole duration of the study period, were already committed to protective behaviours. In addition, low response rates and the characteristics of the sample (mainly young, male, highly educated and white) mean that our findings have to be taken with caution as their generalisability is limited. It would be worth replicating this study with a more representative and larger sample of the population. Another main problem was the high attrition rates, which meant
that our analyses had little power to detect actual effects if there was a real one. We believe this was mainly due to a technical problem experienced with the smartphone app. In addition, we collected data for a period of 4 weeks, which represents a very short time frame, and were not able to collect actual behaviour change in case of a real high air pollution episode, but only intentions. Future similar studies should consider collecting data during periods of higher frequencies of air quality alerts (e.g. in spring, when air pollution tends to be at its highest due to a combination of high temperatures together with factory emissions, urban pollution and ammonia from farms). It would also be important to design studies with a longer follow-up period in order to collect data on longer-term behaviour changes.

Our measurement of actual adherence to the moderate air pollution alert may be inaccurate for several reasons: (a) it was measured by self-reports, which are known to be often an overestimation of actual behaviours compared to objective measurements (Garber et al., 2004); (b) measures of adherence to both preventer and reliever inhalers may also have some degree of inaccuracy as we did not ask lung diseased participants to specify whether they had a prescription to use either or both of the inhalers. However, we tried to overcome this problem by adding a ‘not/applicable’ response option to questions about inhaler use to allow participants to skip non relevant questions; (c) finally, some measures of actual behaviour change may have led to inaccurately low percentages of protective behaviours, as some participants who were already engaged in regular protective behaviours answered negatively to our questions about behaviour change. Moreover, we cannot exclude the effect of potential confounding related to the fact that control and intervention groups received messages with a different frequency (Finitsis et al., 2014).

Some of the additional messages tried to target people with existing heart conditions, but these messages were limited in number in comparison with the respondents with respiratory problems. However, it must be acknowledged that this was a first attempt as the current UK DAQI have very minimal indications for those with cardiac problems (e.g. ‘Follow your doctor’s advice about exercising and managing your condition’).

Further research will have to investigate how to convey accessible information about the health impacts of short term exposure to different air quality levels, as well as the cumulative health impacts of exposure to moderate episodes of air pollution, which is currently not addressed by the UK AQI.

5. Conclusions

The present study found that significantly more respondents in the intervention group (i.e. those who received behaviourally enhanced messages targeting message specificity and psychosocial predictors of behaviour change) had considered making permanent changes to reduce exposure to air pollution at four weeks, compared to the control group receiving the usual UK DAQI messages. This effect was mediated by a reduced perception of not having enough time to follow the health advice received. It was also found that higher worry about air pollution, perceived severity, perceived efficacy of the recommended behaviour and self-efficacy were predictive of self-reported behaviour change at four weeks. Although only a minority of respondents changed actual behaviour in response to a real moderate air quality alert (with no significant differences among experimental groups), among those with a pre-existing lung condition, more respondents in the intervention group reported having used their preventer inhaler compared to the control group.

On the other hand, the two message formats performed similarly when intentions were collected in relation to a hypothetical high air pollution scenario. This study expands the currently limited understanding of how to improve the behavioural impact of existing air quality alerts.

Ethics, consent and permissions

Ethics approval granted by the BDM Research Ethics Panel at King’s College London on the 2nd March 2017 [ref: LRS-16/17-4286]. Given that this research used online surveys, no written consent was taken. However, all potential participants were provided with a detailed participant information sheet, which clearly stated that participation was entirely voluntary, and that completing the research online would indicate their consent to participate.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors’ contributions

DD drafted the manuscript. All authors read and approved the final manuscript.

Acknowledgements

DD conducted the study, following advice from JW, VA, HW, GF and AG provided expert advice and feedback on study design and materials. DD drafted the manuscript, and all other authors read and approved the final manuscript before submission for publication. Ruth Calderwood (Air Quality Manager at City of London Corporation) provided feedback on the study design and supported in advertising the study. Thanks to the City of London Corporation for giving us permission to use the CityAir application for research purposes during August 2017. AG also provided technical support in using the application through the study period. Thanks to Mark Wollard for writing the code for CityAir.
**Appendix A**

**Table A.1**

| Targeted Variable | General population | Sent | At risk - other | Sent | At risk: lung-specific | Sent | At risk: heart-specific | Sent | At-risk: combo | Sent |
|--------------------|--------------------|------|----------------|------|------------------------|------|-------------------------|------|----------------------|------|
| **Perceived severity** | Research into the impact of air pollution on health has confirmed negative short and long-term effects in some people. Short-term effects may include inflammation of the airways. In the long-term air pollution can also worsen heart and lung disease and may lead to a shortened lifespan. | Day 1 | Research into the impact of air pollution on health has confirmed negative short and long-term effects in some people. Short-term effects may include inflammation of the airways. In the long-term air pollution can also worsen heart and lung disease and lead to premature death. | Day 1 | Research into the impact of air pollution on health has confirmed negative short and long-term effects in some people. Short-term effects may include inflammation of the airways. In the long-term air pollution can also worsen heart and lung disease and lead to premature death. | Day 1 | Research into the impact of air pollution on health has confirmed negative short and long-term effects in some people. Short-term effects may include inflammation of the airways. In the long-term air pollution can also worsen heart and lung disease and lead to premature death. | Day 1 |
| **Knowledge and Beliefs about symptoms worsened by air pollution** | Air pollution can make asthma symptoms worse by causing more inflammation in the lungs. | Day 2 | Research shows that when air quality is poor we breathe in pollutants, which can get into the bloodstream and affect your heart, even more for people with heart problems. | Day 2 | Air pollution can make asthma symptoms worse by causing more inflammation in the lungs. Research shows that when air quality is poor we breathe in pollutants, which can get into the bloodstream and affect your heart, even more for people with heart problems. | Day 2 |
| **Perceived susceptibility** | During high and very high air pollution days, everyone is exposed to the potentially harmful air pollution. If you jog, cycle or walk during those days you might be more susceptible to these health effects. | Day 3 | During days of moderate, high or very high air pollution, people like you who have heart or lung problems, might be more susceptible to the harmful health effects of air pollution. These effects can happen even if you don't notice them. | Day 3 | During days of moderate, high or very high air pollution, people like you who have heart or lung problems, might be more susceptible to the harmful health effects of air pollution. These effects can happen even if you don't notice them. | Day 3 | During days of moderate, high or very high air pollution, people like you who have heart or lung problems, might be more susceptible to the harmful health effects of air pollution. These effects can happen even if you don't notice them. | Day 3 |
| **Response efficacy** | Taking a side street route cuts a person's exposure to air pollution by half | Day 5 | Taking a side street route cuts a person's exposure to air pollution by half | Day 5 | Taking a side street route cuts a person's exposure to air pollution by half | Day 5 | Taking a side street route cuts a person's exposure to air pollution by half | Day 5 |
| | Moving your strenuous outdoor physical activity to a less polluted time (e.g. mornings or away from rush hours) is a way to protect yourself from outdoor air pollution and its effect. | Day 7 | Moving your strenuous outdoor physical activity to a less polluted time (e.g. mornings or away from rush hours) is a way to protect yourself from outdoor air pollution and its effect. | Day 7 | Moving your strenuous outdoor physical activity to a less polluted time (e.g. mornings or away from rush hours) is a way to protect yourself from outdoor air pollution and its effect. | Day 7 | Moving your strenuous outdoor physical activity to a less polluted time (e.g. mornings or away from rush hours) is a way to protect yourself from outdoor air pollution and its effect. | Day 7 |

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Table A.1 (continued)

| Targeted Variable                        | General population | Sent | At risk - other | Sent | At risk: lung-specific | Sent | At risk: heart-specific | Sent | At-risk: combo | Sent |
|------------------------------------------|--------------------|------|----------------|------|------------------------|------|------------------------|------|--------------|------|
| During days of poor air quality, reducing strenuous outdoor physical activity is a way to protect yourself from outdoor air pollution and its harmful effect. | Day 9              |      |                |      |                        |      |                        |      |              |      |
| During days of poor air quality, reducing strenuous outdoor physical activity is a way to protect yourself from outdoor air pollution and its harmful effect. | Day 9              |      |                |      |                        |      |                        |      |              |      |
| During poor air quality you do not need to stop doing physical activity. | Day 9              |      |                |      |                        |      |                        |      |              |      |
| During poor air quality you do not need to stop doing physical activity. | Day 11             |      |                |      |                        |      |                        |      |              |      |
| The CityAir App can help you find side street routes, which do not necessarily add to your total travel time, and may give you a more pleasant journey. | Day 13             |      |                |      |                        |      |                        |      |              |      |
| The CityAir App can help you find side street routes, which do not necessarily add to your total travel time, and may give you a more pleasant journey. | Day 13             |      |                |      |                        |      |                        |      |              |      |
| Day 13 The CityAir App can help you find side street routes, which do not necessarily add to your total travel time, and may give you a more pleasant journey. | Day 15             |      |                |      |                        |      |                        |      |              |      |
| People who are able to move outdoor physical activities to the mornings or side roads can protect themselves from air pollution. Start by making one change to your next scheduled activity (e.g. start by walking as far from the kerb as possible) and build up from there. | Day 17             |      |                |      |                        |      |                        |      |              |      |
| Day 17 People who are able to move outdoor physical activities to the mornings or side roads can protect themselves from air pollution. Start by making one change to your next scheduled activity (e.g. start by walking as far from the kerb as possible) and build up from there. | Day 17             |      |                |      |                        |      |                        |      |              |      |
| Day 17 The CityAir App can help you find side street routes, which do not necessarily add to your total travel time, and may give you a more pleasant journey. | Day 15             |      |                |      |                        |      |                        |      |              |      |
| People who are able to move outdoor physical activities to the mornings or side roads can protect themselves from air pollution. Start by making one change to your next scheduled activity (e.g. start by walking as far from the kerb as possible) and build up from there. | Day 13             |      |                |      |                        |      |                        |      |              |      |
| People who are able to move outdoor physical activities to the mornings or side roads can protect themselves from air pollution. Start by making one change to your next scheduled activity (e.g. start by walking as far from the kerb as possible) and build up from there. | Day 13             |      |                |      |                        |      |                        |      |              |      |
| People who are able to move outdoor physical activities to the mornings or side roads can protect themselves from air pollution. Start by making one change to your next scheduled activity (e.g. start by walking as far from the kerb as possible) and build up from there. | Day 13             |      |                |      |                        |      |                        |      |              |      |
| People who are able to move outdoor physical activities to the mornings or side roads can protect themselves from air pollution. Start by making one change to your next scheduled activity (e.g. start by walking as far from the kerb as possible) and build up from there. | Day 13             |      |                |      |                        |      |                        |      |              |      |
| People who are able to move outdoor physical activities to the mornings or side roads can protect themselves from air pollution. Start by making one change to your next scheduled activity (e.g. start by walking as far from the kerb as possible) and build up from there. | Day 13             |      |                |      |                        |      |                        |      |              |      |
| People who are able to move outdoor physical activities to the mornings or side roads can protect themselves from air pollution. Start by making one change to your next scheduled activity (e.g. start by walking as far from the kerb as possible) and build up from there. | Day 13             |      |                |      |                        |      |                        |      |              |      |

Air pollution can be high or very high, even if there are no odours or visible smog. Official environment indicators provide a more precise measure of air quality.

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Table A.1 (continued)

| Targeted Variable                | General population | Sent | At risk - other | Sent | At risk: lung-specific | Sent | At risk: heart-specific | Sent | At risk: combo | Sent |
|----------------------------------|--------------------|------|-----------------|------|------------------------|------|------------------------|------|----------------|------|
| **Action planning**<sup>a</sup>  | Using this App,    | Day 19 |             |      |                        |      |                        |      |                |      |
|                                  | check out the      |      |             |      |                        |      |                        |      |                |      |
|                                  | average air quality|      |             |      |                        |      |                        |      |                |      |
|                                  | on the roads you   |      |             |      |                        |      |                        |      |                |      |
|                                  | usually use. By    |      |             |      |                        |      |                        |      |                |      |
|                                  | doing this, you    |      |             |      |                        |      |                        |      |                |      |
|                                  | can plan           |      |             |      |                        |      |                        |      |                |      |
|                                  | alternative routes. |      |             |      |                        |      |                        |      |                |      |
| **Before you go out**            | walking, jogging or| Day 21 |             |      |                        |      |                        |      |                |      |
|                                  | cycling check our  |      |             |      |                        |      |                        |      |                |      |
|                                  | App to find less   |      |             |      |                        |      |                        |      |                |      |
|                                  | polluted areas     |      |             |      |                        |      |                        |      |                |      |
|                                  | where exercising.  |      |             |      |                        |      |                        |      |                |      |
|                                  | Start by exploring  |      |             |      |                        |      |                        |      |                |      |
|                                  | green areas and    |      |             |      |                        |      |                        |      |                |      |
|                                  | parks close to your|      |             |      |                        |      |                        |      |                |      |
|                                  | house or office.   |      |             |      |                        |      |                        |      |                |      |
|                                  | Day 21             |      |             |      |                        |      |                        |      |                |      |
|                                  | Before you go out  |      |             |      |                        |      |                        |      |                |      |
|                                  | walking, jogging or| Day 21 |             |      |                        |      |                        |      |                |      |
|                                  | cycling check our  |      |             |      |                        |      |                        |      |                |      |
|                                  | App to find less   |      |             |      |                        |      |                        |      |                |      |
|                                  | polluted areas     |      |             |      |                        |      |                        |      |                |      |
|                                  | where exercising.  |      |             |      |                        |      |                        |      |                |      |
|                                  | Start by exploring  |      |             |      |                        |      |                        |      |                |      |
|                                  | green areas and    |      |             |      |                        |      |                        |      |                |      |
|                                  | parks close         |      |             |      |                        |      |                        |      |                |      |
|                                  | to your house or    |      |             |      |                        |      |                        |      |                |      |
|                                  | office.             |      |             |      |                        |      |                        |      |                |      |
|                                  | Day 21             |      |             |      |                        |      |                        |      |                |      |
|                                  | Before you go out  |      |             |      |                        |      |                        |      |                |      |
|                                  | walking, jogging or| Day 21 |             |      |                        |      |                        |      |                |      |
|                                  | cycling check our  |      |             |      |                        |      |                        |      |                |      |
|                                  | App to find less    |      |             |      |                        |      |                        |      |                |      |
|                                  | polluted areas     |      |             |      |                        |      |                        |      |                |      |
|                                  | where exercising.  |      |             |      |                        |      |                        |      |                |      |
|                                  | Start by exploring  |      |             |      |                        |      |                        |      |                |      |
|                                  | green areas and    |      |             |      |                        |      |                        |      |                |      |
|                                  | parks close         |      |             |      |                        |      |                        |      |                |      |
|                                  | to your house or    |      |             |      |                        |      |                        |      |                |      |
|                                  | office.             |      |             |      |                        |      |                        |      |                |      |
|                                  | Day 21             |      |             |      |                        |      |                        |      |                |      |
|                                  | During days of poor |      |             |      |                        |      |                        |      |                |      |
|                                  | air quality, if     |      |             |      |                        |      |                        |      |                |      |
|                                  | you have a reliever |      |             |      |                        |      |                        |      |                |      |
|                                  | inhaler, remember  |      |             |      |                        |      |                        |      |                |      |
|                                  | to carry it with you.|      |             |      |                        |      |                        |      |                |      |
|                                  | Day 22             |      |             |      |                        |      |                        |      |                |      |
|                                  | Using this App,     |      |             |      |                        |      |                        |      |                |      |
|                                  | check out the      |      |             |      |                        |      |                        |      |                |      |
|                                  | average air quality |      |             |      |                        |      |                        |      |                |      |
|                                  | on the roads you    |      |             |      |                        |      |                        |      |                |      |
|                                  | usually use. By     |      |             |      |                        |      |                        |      |                |      |
|                                  | doing this, you     |      |             |      |                        |      |                        |      |                |      |
|                                  | can plan           |      |             |      |                        |      |                        |      |                |      |
|                                  | alternative routes. |      |             |      |                        |      |                        |      |                |      |
|                                  | If you have heart   |      |             |      |                        |      |                        |      |                |      |
|                                  | problems, it’s very  |      |             |      |                        |      |                        |      |                |      |
|                                  | important that you  |      |             |      |                        |      |                        |      |                |      |
|                                  | take your medicines |      |             |      |                        |      |                        |      |                |      |
|                                  | on a daily basis as  |      |             |      |                        |      |                        |      |                |      |
|                                  | prescribed by your  |      |             |      |                        |      |                        |      |                |      |
|                                  | doctor.             |      |             |      |                        |      |                        |      |                |      |
|                                  | Before you go out   |      |             |      |                        |      |                        |      |                |      |
|                                  | walking, jogging or | Day 21 |             |      |                        |      |                        |      |                |      |
|                                  | cycling check our   |      |             |      |                        |      |                        |      |                |      |
|                                  | App to find less    |      |             |      |                        |      |                        |      |                |      |
|                                  | polluted areas     |      |             |      |                        |      |                        |      |                |      |
|                                  | where exercising.  |      |             |      |                        |      |                        |      |                |      |
|                                  | Start by exploring  |      |             |      |                        |      |                        |      |                |      |
|                                  | green areas and    |      |             |      |                        |      |                        |      |                |      |
|                                  | parks close         |      |             |      |                        |      |                        |      |                |      |
|                                  | to your house or    |      |             |      |                        |      |                        |      |                |      |
|                                  | office.             |      |             |      |                        |      |                        |      |                |      |
|                                  | Day 22             |      |             |      |                        |      |                        |      |                |      |
| Total n.                         | 11                 | 11    | 16             | 13   | 16                     | 16   |                        |      |                |      |

The table reports the specific variable targeted by the messages, who was the target of the messages and when the messages were sent. The total of messages sent for each group is reported at the bottom of the table. Although the majority of massages targeting the at-risk group were identical, some were slightly adjusted depending on whether people had a pre-existing lung and/or heart disease, or if they reported to be at risk for other conditions including old age. This was to make sure that participants were not receiving messages irrelevant to them, as this may lead to confusion, loss of interest, and mistrust (e.g. (Sillence et al., 2004)). The average readability scores were 9.3 (i.e. easily understood by 14 to 15 year olds) and 9.8 (i.e. easily understood by 15 to 16 year olds), for the general population and at-risk groups (all messages considered) respectively.

<sup>a</sup> This refers to the behaviour change technique (BCT) coded 1.4, which prompted planning of performance of the relevant behaviours (including context and timing) (Michie et al., 2013).

**Appendix B. Health messages development**

All health messages were developed to target specific psychosocial factors identified in a previous systematic review (D’Antoni et al., 2017). To ensure accuracy of the messages targeting knowledge about air pollution and its health impact, and information about the efficacy of the health advice provided, all health messages were reviewed by experts from the KCL Environmental Research Group (ERG). These messages together with all research materials and questionnaires were also tested through Patient and Public Involvement (PPI) workshops. In particular, two workshops were held in May and July 2017. The first was conducted with five patients with severe respiratory conditions, from St Thomas Hospital, London; the second with seven members of the general public in London. Participants in both workshops appreciated the importance and potential implications of the study, and considered the research participant involvement to be appropriate. Based on feedback received, some health messages were slightly reworded to increase their readability. Suggestions were also made to clarify parts of the participant information sheet. In addition, the study design was slightly modified to adjust the frequency and sending times for the additional health messages, as well as how many questionnaire reminders to send and when. In particular, as result of feedback from the PPI panel with respiratory conditions, it was decided that the additional messages for the study participants in the at-risk groups were to be sent with high frequency (the PPI panel was keen for messages to be sent daily).
Appendix C

Fig. C.1. The research study launched via the ‘CityAir’ application: (a) the notification about the study, with functions for 1. opting in or out or setting a reminder, 2. indicating existing health conditions in order to receive targeted advice, and 3. accessing the participant information sheet; (b) the participant information sheet (also available through the study period via the CityAir app ‘News’ section); (c) the hypothetical high air pollution forecast scenario, as part of the baseline questionnaire, and (d) the relative health advice (in this case for at risk individuals). Respondents were given the chance to complete the questionnaire at their more convenient time by using the ‘Remind later’ option.
### Table D.1
Summary of the questionnaire items used in the study.

| Timing | Measurement | How it was measured |
|--------|-------------|---------------------|
| First online questionnaire  
– After reading hypothetical high air pollution scenario | Baseline intentions\(a\) to adopt protective behaviours in response to hypothetical, high air pollution alert | Assuming the situation described was happening right now, how much would you agree with the following statements?  
- I intend to follow the recommendations received with the air alert to reduce exposure to air pollution  
- I will avoid going outdoors  
- I intend to reduce length or level of my physical activity outdoors  
- I intend to change my travel route  
- I intend to change my exercise location  
- I intend to change the time when I travel  
- I intend to change the time when I exercise outdoors |
| Baseline medication adherence intentions\(a\) | For people with lung problems only:  
- I intend to use my preventer inhaler daily  
- I intend to carry my reliever inhaler with me |
| Other baseline intention\(a\)  
(not advised behaviours) | - I will wear a mask as a protection from air pollution  
- I intend to reduce length or level of my physical exercise indoors |
| Previous protective behaviour\(b\) | - In the past 4 weeks, how often have you taken action to reduce exposure to air pollution, I response to hearing or reading an air quality forecast?  
- In the last 4 weeks, to reduce your exposure to air pollution, have you considered making permanent changes to your daily travel route or exercise place and time?  
- In the last 4 weeks, how often have you checked air quality information before doing physical activity outdoors?\(b\) |
| Planning | Physical activity\(d\)  
- To stay healthy, the NHS recommends at least 150 min of moderate physical activity (e.g. cycling, fast walking, swimming) every week (e.g. 30 min 5 days a week). Based on this, how physically active were you in the last week? |
| Symptoms\(c\) | Alert recall\(c\)  
- Recently we sent you an air quality alert about poor air quality. What was the level of air pollution reported? |
| Air alert period –  
online questionnaires | Actual Behaviour change\(c\)  
In response to receiving the air quality alert:  
- I reduced length or level of my physical activity outdoors  
- I changed my travel route  
- I changed my exercise location  
- I changed the time when I travelled  
- I changed the time when I exercised outdoors  
- If you answered no, please report the reasons [text box]. |
| Medication adherence\(c\) | If you have lung problems:  
- I used my preventer inhaler daily  
- I carried my reliever inhaler with me when going outdoors.  
- If you answered no, please report the reasons [text box].  
(continued on next page)
| Timing                      | Measurement                                                                 | How it was measured                                                                                           |
|-----------------------------|------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|
| Final online questionnaire  | Behaviour change at 4 weeks<sup>b</sup>                                      | - In the past 4 weeks, how often have you taken action to reduce exposure to air pollution, I response to hearing or reading an air quality forecast? |
|                             | Physical activity<sup>d</sup>                                                 | - To stay healthy, the NHS recommends at least 150 min of moderate physical activity (e.g. cycling, fast walking, swimming) every week (e.g. 30 min 5 days a week). Based on this, how physically active were you in the last week?<sup>c</sup> |
|                             | Action planning                                                               | - In the last 4 weeks, to reduce your exposure to air pollution, have you considered making permanent changes to your daily travel route or exercise place and time?<sup>c</sup> |
|                             | Worry<sup>a</sup>                                                            | - The information received through the CityAir app made me worry about the possibility of suffering health effects from exposure to air pollution |
|                             | (ρ<sub>uu</sub> = 0.76)                                                      | - The information received through the CityAir app made me nervous and tense about the possibility of suffering health effects from exposure to air pollution |
|                             | Severity<sup>a</sup>                                                         | - Air pollution is a severe threat to my health                                                             |
|                             | Conditional susceptibility<sup>a</sup>                                         | - How likely do you think you are to suffer from health effects due to air pollution if you do not take any action to reduce exposure? |
|                             | (ρ<sub>uu</sub> = 0.86)                                                      | - How likely do you think people of your same age and sex are to suffer from health effects due to air pollution if they do not take any action to reduce exposure? |
|                             | Response efficacy<sup>a</sup>                                                | - Following the health advice received through the CityAir app is effective in protecting me from exposure to air pollution |
|                             | Medication response efficacy<sup>a</sup>                                       | - If you have asthma:                                                                                       |
|                             | (ρ<sub>uu</sub> = 0.95)                                                      | - Taking my preventer medications daily is effective in helping me to control my asthma                      |
|                             | Self-efficacy<sup>a</sup>                                                    | - Carrying my reliever medication with me is an effective way to protect my health                          |
|                             | (ρ<sub>uu</sub> = 0.96)                                                      | - I am confident I would be able to follow the health advice received through the CityAir app, if I wanted to |
|                             | Medication self-efficacy<sup>a</sup>                                         | - Items adapted from Witte et al. (Witte et al., 2001) and Rhode et al. (Rhodes et al., 2006)                  |
|                             | (ρ<sub>uu</sub> = 0.96)                                                      | - If you have asthma:                                                                                       |
|                             | If you have asthma:                                                         | - I am confident I would be able to take my preventer inhaler every day, if I wanted to                      |
|                             | Response costs<sup>a</sup>                                                   | - I am confident I would be able to remember to carry my reliever inhaler with me during days of poor air quality, if I wanted to |
|                             | (ρ<sub>uu</sub> = 0.95)                                                      | - I do not have enough time to follow the health advice received through the CityAir app                      |
|                             | Taking side roads makes my journey too long                                  | - Taking side roads makes my journey too long                                                               |
|                             | Medication response costs<sup>a</sup>                                        | - Using the preventer inhaler daily is not safe                                                             |
|                             | (ρ<sub>uu</sub> = 0.95)                                                      | - Using the preventer inhaler daily makes me dependent on it                                               |
|                             | Unwanted consequences of intervention<sup>a</sup>                             | - In the last 4 weeks I stopped exercising altogether due to receiving alerts about poor air quality         |
|                             | Sensory cue prevalence<sup>a</sup>                                           | - In the last 4 weeks, I made an emergency/unplanned visit to A&E or visited my GP due to symptoms caused by air pollution |
|                             | Credibility<sup>a</sup>                                                      | - I trust my own perception of air quality more than any official air quality alert                          |
|                             | (Meyer's credibility index (Meyer, 1988; McComas and Trumbo, 2001) (α = 0.67) |                                                                                                             |
|                             | Intentions<sup>a</sup> to adopt protective behaviour in response to hypothetical, high air pollution alert | [After reading again the high air pollution hypothetical scenario and tailored advice]                         |
|                             | Medication adherence intentions<sup>a</sup>                                  | - I intend to follow the recommendations received with the air alert to reduce exposure to air pollution      |
|                             | (for people with lung problems only):                                        | - I will avoid going outdoors                                                                               |
|                             | Other intentions (not advised behaviours)<sup>a</sup>                        | - I intend to use my preventer inhaler daily                                                                 |
|                             | (on a 5-point scale. Demographic data was collected for all the participants in the first questionnaire. | - I intend to carry my reliever inhaler with me                                                             |
|                             | Notes:                                                                      | - I will wear a mask as a protection from air pollution                                                    |
|                             | To measure reliability of a two-item scales Spearman-Brown statistic was used as both Cronbach's alpha and Pearson correlation are considered less accurate estimate of reliability in such cases (for an overview see (Bisinga et al., 2013)). |                                                                                                             |
Appendix E

Fig. E.1. CONSORT flow diagram describing the participants’ progress through the trial.
Note: * Of 91 total responses submitted, the following were excluded: incomplete & not matched to any questionnaire (n = 5); not matched to any other questionnaire (n = 4).

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