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A new portable sampler to monitor pollen at street level in the environment of patients

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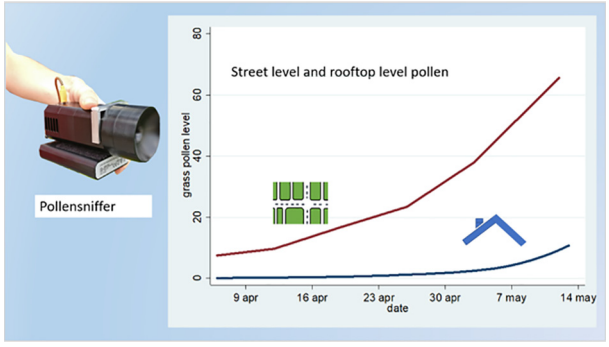
HIGHLIGHTS

- An easy-to-use portable pollen sampler is developed and validated
- At street level grass and birch pollen is distributed unevenly throughout a city
- Grass/birch pollen is detected weeks earlier at street- compared to rooftop level

GRAPHICAL ABSTRACT



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ABSTRACT

Allergic rhinitis caused by pollen exposure is one of the most common allergic diseases. Therefore monitoring pollen levels in ambient air is an important tool in research and health care. Most European monitoring stations collect airborne pollen at rooftop levels for measurements in the larger surrounding of the sampling station, and not in the direct environment of sensitized subjects. Here we present the development and evaluation of a portable pollen sampler, called "Pollensniffer", that was designed to collect pollen in the immediate environment of allergic subjects. Validation of the Pollensniffer against the standard volumetric pollen sampler showed for most pollen types high correlations between the number of pollen collected by those two devices (Spearman's Correlation Coefficient > 0.8); the Pollensniffer appeared to collect on average 5.8 times more pollen per hour than the static sampler. Pollen monitoring was performed using this Pollensniffer at street level at 3 different locations in the city of Leiden during 22 weeks in 2017 and 21 weeks in 2018, during three 15-min periods a day and at one day in the week. The results showed that the pollen levels for birch and grass pollen can significantly differ from location to location and per time of day. Furthermore, the Pollensniffer measurements at street level showed that birch and grass pollen grains were detected 1 1/2 and 2–3 weeks, respectively, before detection at rooftop level. The street measurements show that allergic subjects can encounter varying pollen levels throughout the city and that they can be exposed to grass and birch pollen and may experience hay fever symptoms, even before the sampler at rooftop level registers these pollen.

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1. Introduction

Thirty to forty percent of the Europeans suffers from the symptoms of allergic rhinitis (Blomme et al., 2013), and although sometimes trivialized, it is considered as a major health problem. The most common symptoms of allergic rhinitis are itchy or runny nose, sneezing, blocked nose and commonly co-existing non-nasal symptoms such as itchy and watery eyes; importantly, also quality of life, sleep and work productivity is affected (Bousquet et al., 2006). Although these symptoms are bothersome, about 10% of the patients never consult their doctor for their problems, and most patients treat their symptoms by self-medication (Maurer and Zuberbier, 2007). Yet, it is known that inadequate treatment of allergic rhinitis can trigger the development of asthma (Bousquet et al., 2008).

Besides these medical and social aspects, also the economic impact of allergic rhinitis is considerable: the total mean of health care and indirect costs (absenteeism and presenteeism) amounts to €2326,70 per allergic rhinitis patient-year (Colas et al., 2017).

Pollen exposure is a major trigger for allergic rhinitis symptoms. For both patients and their treating physicians, it is relevant to know when allergenic pollen is in the air. Therefore, more than 500 pollen monitor stations in Europe monitor the pollen grains that are present in the air on a daily basis (Buters et al., 2018). The pollen samplers are located at a height of 10–30 m above ground level to collect the different pollen types that are released by the plants present in the region and is thus representative for the larger surroundings. Monitoring pollen at this height is justified since sampling at near ground level would favour the collection of more locally produced pollen and would show more daily fluctuations, while at 10 m and higher above ground level the pollen concentrations are more stable (Galán et al., 2014; Rojo et al., 2019). However, patients are mostly exposed at street level, and knowledge on the distribution of aero-allergens at this level is limited. Some studies monitored pollen at different height levels and compared the street level measurement using a stationary sampler with the same kind of sampler located at rooftop level. Most of these studies showed that the pollen concentrations at rooftop level correlate well with the pollen concentrations monitored at street level, although in general the concentrations were higher at street level (Bastl et al., 2019; Rantio-Lehtimäki et al., 1991; Rojo et al., 2019; Spieksma et al., 2000). One study showed that at so called 'street canyon environments' in urban areas, grass pollen concentrations tended to be lower (Peel et al., 2014a). Studies on the pollen distribution at street level in cities are limited. In these studies different sampling methods have been used, but they all indicate that highly variable pollen concentrations exist at different locations within cities at street level (Ishibashi et al., 2008; Katz and Carey, 2014; Skjøth et al., 2013; Werchan et al., 2017).

In order to be able to monitor pollen at different locations, easy-to-use, portable samplers are needed. Furthermore, such samplers can be used to monitor pollen or other allergens in the direct environment of the patient. Fiorina et al. (Fiorina et al., 2003) described that aerobiological sampling in the direct environment of two asthmatic patients, for whom the causative allergen was difficult to identify, revealed the responsible allergen. In that pilot study, a battery operated portable sampler (PARTRAP) was used (Fiorina et al., 1997). In the past decades several other personal samplers have been described, but – to our knowledge- these devices, including the PARTAP, are not commercially available (Peel et al., 2013; Renstrom et al., 2002; Werchan et al., 2018; Yamamoto et al., 2015). Furthermore, the user-friendliness and the efficacy of these devices varies; nasal samplers (Renstrom et al., 2002) are placed in the nostrils of the nose and depend on breathing, and the Personal AeroAllergen Sampler (PAAS) (Yamamoto et al., 2007) relies on passive pollen collection and is carried around the neck for a longer period, which both may not be very comfortable. The currently available transportable samplers (Peel et al., 2014b) are made for installation on the floor, but not specifically for portable use and furthermore has a lower efficiency than a static 7-day recording sampler.

Therefore, in this paper we developed a portable sampler, that is ease-to-use to collect allergens at different locations, especially in the environment of allergic patients. Although the constructed device, called Pollensniffer, can also collect other bioaerosols like fungal spores, in this study we focussed on pollen. The Pollensniffer was validated by comparison to a standard Hirst type pollen sampler (Hirst, 1952), and used to study the distribution of birch and grass pollen at street level, since here the patients will come into contact with the pollen. In the analysis of the data we focussed on issues that are relevant for the allergic rhinitis patients such as (i) the differences in pollen levels at different locations in the city; and (ii) the timing of exposure to the first pollen grains of the season at street level.

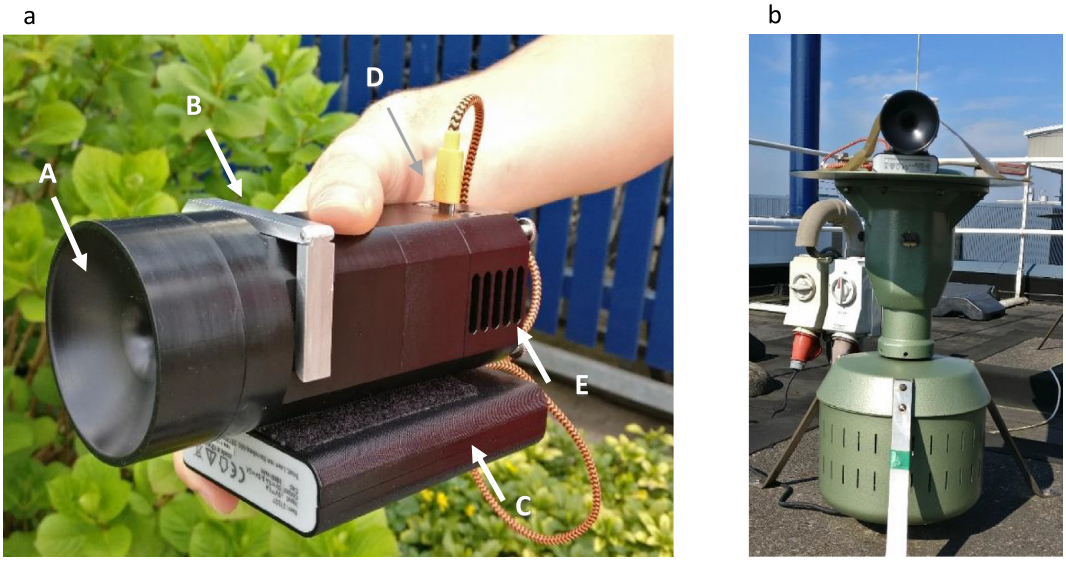


Fig. 1. a. Pollensniffer with the conical inlet (A) and the aluminium closing of the opening for the sample holder (B). A connector cable connects a power bank (C) to a micro-USB connector (D) in the Pollensnifffer. The airstream generated by the ventilator inside the Pollensniffer leaves the Pollensniffer at openings at the rear end (not shown) and at three backsides (e.g. E). b. The Pollensniffer (PS1) mounted on the rain cover of the static sampler on the roof of the LUMC.

2. Materials and methods

2.1. Description of the Pollensniffer

The Pollensniffer is a portable device to monitor airborne pollen with the following dimensions: diameter 6 cm; length 15 cm; weight 408 g (Pollensniffer) + 205 g (power bank). The body of this low-volume Pollensniffer (Fig. 1a) consists of four elements that were printed in a 3D printer using POM (polyoxymethylene). The technical drawings are shown in Supplementary Fig. S1.Three elements at the back (Fig. S1, b, d and e) were connected using 4 long thin bolts. The inlet is placed onto the body via a bayonet mount. The inlet (Fig. S1,a) has a conical shape and behind the inlet, a static sample holder is inserted. This sample holder can be placed into the Pollensniffer via an opening on the side. This opening is secured by an aluminium handle (Fig. 1a, arrow B).

The static sample holder contains a 4 cm-long, 2.5 cm-wide carrier glass-slide on which a Vaseline-coated Melinex strip (Burkard Manufacturing Co. Limited, UK) is mounted to collect the pollen, that passed the inlet. Behind the sample holder, a ventilator generates an air-stream into the Pollensniffer. Pollen grains that are drawn in, are trapped onto the Vaseline strip. The air stream passes through the Pollensniffer and escapes via openings at the rear end (Fig. 1a, arrow E). Electronics to power the ventilator are located behind the ventilator. Using a connector cable, a power bank (Fig. 1a, C; Intenso S10000, Germany) is connected to the Pollensniffer via a micro-USB connector (Fig. 1a, D). The ventilator generates an airflow through the inlet (10 mm) and the pollen grains are drawn inwards and collide with the Vaseline-coated Melinex tape and stick into the Vaseline. Although an estimated 90% of the pollen grains are deposited on the Vaseline tape in an approximate 12 mm circle behind the inlet, also all pollen grains collected on the tape outside this circle are counted (see also later).

To measure the air flow that passed through the Pollensniffer an electronic flow cell (Honeywell AWM5102 VN airstream sensor, North Carolina, USA) was air-tightly connected to the conical inlet of the Pollensniffer via a funnel. The flow appeared to be constant during the whole operating time of the power bank, i.e. 5–6 h.

The Pollensniffer was evaluated for its user-friendliness by participants of a local theatre and music festival in Schipborg, Netherlands (FestiValderAa, 7–9 July 2017). Fifteen random, voluntary participants used the Pollensniffer by holding it in their hand during a short walk and completed a small questionnaire on the user-friendliness of the device.

2.2. Validation of the Pollensniffer

On the roof of the 6th floor of the Leiden University Medical Center (LUMC; west part of the Netherlands), approx. 22 m above ground level two static traps (Burkard Manufacturing Co. Limited, UK) were present. One sampler was used for the routinely monitoring of the daily pollen concentrations (see later), while on the other sampler the firstly constructed Pollensniffer (PS1) was mounted on the rain-cover. The inlets of the Pollensniffer and the static sampler were both facing the wind guided by the wind vane of the static sampler (Fig. 1b). As shown in Fig. S1 the inlet of the Pollensniffer has a conical shape and a round inlet with a 10 mm diameter. The static sampler has a standard rectangular inlet of 14 × 2 mm. Both devices collected pollen during 1 or 2 h periods from February 28th to April 4th 2017. Forty-one samples for each of the devices were collected on warm, dry days, anticipating high levels of pollen.

Following manufacturing of the first Pollensniffer (PS1), another four Pollensniffers (PS2, PS3, PS4, and PS5) were constructed. The performance of these Pollensniffers was compared among each other. To this end, the five Pollensniffers were mounted on a rack (15 cm height) at a distance of 20 cm from each other on the roof of the LUMC. They were allowed to collect pollen for 30 min periods on June 13th and 19th, 2017, resulting in 8 different samples for each of the five Pollensniffers. In this period mainly Poaceae and Urticaceae pollen were present and used for the analysis. All Poaceae and Urticaceae pollen present on the slides were counted.

2.3. Pollen monitoring at street- and rooftop level

Rooftop level pollen samples were collected with one of the static 7-day volumetric spore trap continuously. At street level, pollen were collected by the Pollensniffer from April 6th to September 5th in 2017 and February 7th to June 29th in 2018. Three locations in the city of Leiden were selected (Fig. 2): (i) in a main shopping street in Leiden (=City Center) without any plants or trees, except for Linden trees (*Tilia*) in the side way; (ii) on an open space in a park within the city canal boundaries (Huigpark) with a stretch of grass and a diversity of trees, like *Aesculus, Salix, Betula, Platanus, Populus, Sorbus,* and *Taxodium distichum*; and (iii) on an open space in a park more at the border of the city (Kweeklust) with a small grass area and several trees *like Platanus, Populus, Salix, Taxodium distichum,* and bushes like *Corylus.* The birch tree species in the surroundings of the monitoring locations are mapped and shown in Supplementary Fig. S2. An overview of the birch species present in an approximately 500 m circle around the monitor locations is as follows: for the City Center location only a few *Betula* species are present in a 500 m circle, i.e. *B. pendula* (8 trees), *B. papyfrifera* (6 trees) and *B. ermanii* (6 trees). For the Huigpark location hardly any *Betula* species are present at the south side of the park, but at the north side several *B. pendula* species are found e.g. *B. pendula* (60 trees), *B. papyrifera* (15 trees), *B. ermanii* (6 trees), *B. nigra* (30 trees) and *B. utilis* (17 trees). In the surroundings of Kweeklust (within a 500 m circle) at the north side of the city, hardly any *Betula* trees are present but in the streets on the other sides different *Betula* species can be found, i.e. *B. pendula* (43 trees), *B. ermanii* (4 trees), *B. papyrifera* (5 trees), *B. utilis* (2 trees), *B. pubescens* (8 trees) and *B. nigra* (3 trees). When focussing on grass in the surroundings of the monitoring locations it is clear that for the City Center very little grass is present except for some well-maintained grass areas at approx. 400 m from the location. Also at the locations in the parks, the grass areas are well maintained. Only close to Kweeklust there are some grass banks that are mowed only twice a year (early July and half September).

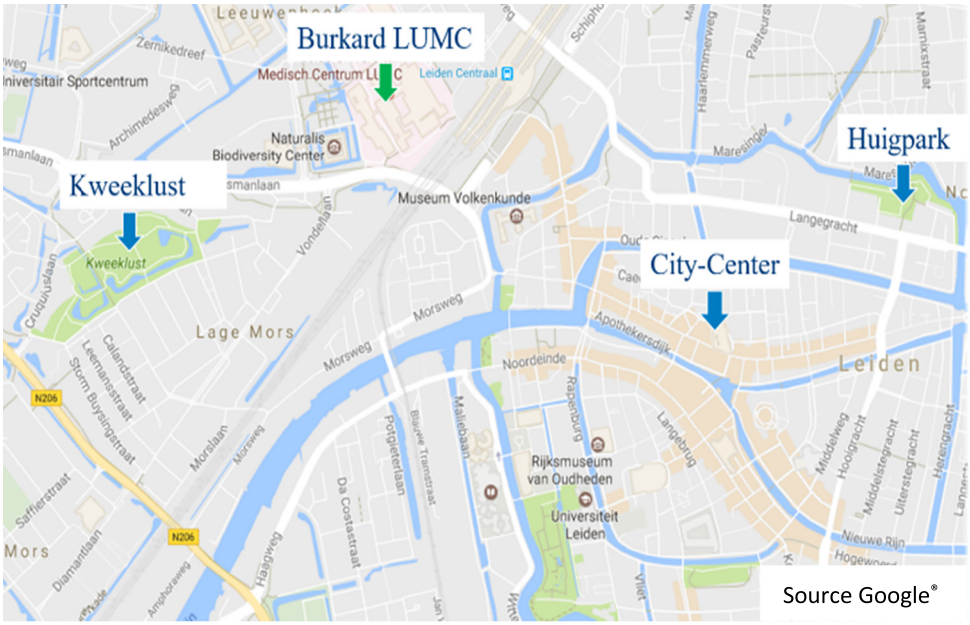
At each location, pollen were sampled for 15 min in the morning (9–10.30 h), in the early afternoon (12.30–14.00 h) and early evening (16.30–17.00 h) during one day in the week. The Pollensniffer was hand-held by a standing person, resulting in a measuring height of approximately 1 to 1.20 m. For the street level measurements Pollensniffer PS1 was used. The day varied depending on the weather; especially dry, sunny days were selected for measurements unless this was not possible. At each location weather parameters like temperature, wind speed and rain were recorded.

In the static sampler as well as in the Pollensniffer, the pollen grains were collected on a Melinex strip covered with Vaseline. The strip was stained by safranin (0.002% *w*/*v*) solution and mounted on a microscopic slide (Galán et al., 2014).

For the daily pollen concentrations the microscopic slides from the static sampler (rooftop level counts) were scanned in three longitudinal bands corresponding to 1 m^3 collected air in 24 h, to obtain daily pollen concentrations (grains/m^3, 24 h) (de Weger et al., 2013; Galán et al., 2017). On the strips of the Pollensniffer, all pollen collected were microscopically differentially counted.

For the validation experiments, the start and the end of each measurement with the static sampler was marked on the Vaseline strip. In contrast to the analysis of daily pollen concentrations where defined areas are being counted, in this analysis all pollen present on the strip between these marks were counted. So in the validation experiment all pollen collected on the tape in the static sampler were compared to all pollen collected on the tape in the Pollensniffer. For the validation

a



b

Fig. 2. a. Map of the city of Leiden showing the location of the roof top level static sampler and the locations of the street level measurements. b. The three locations of the street level measurements, City Center, Huigpark and Kweeklust.

experiments, the results obtained from the Pollensniffer samples and the static sampler were expressed as pollen counts and not as pollen concentrations, since the counts were not related to the sample volume. The sample volume is dependent on the flow rate of the device and we could not use the same device to measure the flow rate in the static sampler and the Pollensniffer since the inlets are different. Furthermore,

Oteros et al. (Oteros et al., 2017) showed that there is a large variation in flow rates measured in routinely used Hirst type samplers. Since we used different devices and comparing flow rates was not possible due to technical restrictions, we carefully standardized sample collection by using a strict protocol concerning duration and time of collection, height at which pollen were collected, and position of collection by directing the inlet of the Pollensniffer facing the current wind direction. Subsequently all pollen present in the sample were microscopically counted and compared.

An overview of the different experiments is provided in Table S1.

2.4. Analysis of data

For the analysis of the validation experiments a correlation analysis was performed to assess the strength of the relationship between the pollen collected by the Pollensniffer and the static pollen sampler. Since a Shapiro-Wilk test showed that neither the original nor the log-transformed pollen data of both samplers were normally distributed, Spearman's correlation coefficient was used. Differences and correlations were considered statistically significant at $p < .05$. For the calculation of the average difference between the pollen collected by the Pollensniffer and the static sampler, a regression analysis was performed using the counts of all individual pollen types.

For the comparison of the 5 individual Pollensniffers the mean and standard deviations of the 8 measurements were calculated. A one way analysis of variance (ANOVA) was performed on the log transformed data, since the log transformed data of this experiment were normally distributed according to the Shapiro-Wilk test.

For the comparison between rooftop level and street level measurements, the daily concentrations of the static sampler were compared to the sum of the street level measurements of the three locations in the morning, the early afternoon and the early evening (the sum of 9 measurements per day). In order to compare the timing of the first seasonal pollen collected by the roof top static sampler and of the first seasonal pollen collected by Pollensniffer at street level, we compared the day at which more than 3 grains/m^3 were collected by the static sampler and when more than 3 grains were collected by the Pollensniffer. This is an arbitrary threshold with the rationale that 1 or 2 pollen can be coincidental and a count of 4 pollen or more is more robust.

All statistical analyses were performed using the statistical software package STATA 14.2 (StataCorp, TX, USA).

3. Results

3.1. General use of the Pollensniffer

The air flow through the Pollensniffers appeared to be very stable during the operating time of the power bank (5–6 h). Using an electronic air flow sensor, the air flow was measured in 5 individual Pollensniffers (Supplement Table S2.) The air flow appeared to depend on the shape of sample holder used. The sample holder was slightly modified in Pollensniffers PS2-PS5 resulting in an increase in air flow through the device from 7.5 l/min to 8.3–9.2 l/min.

The user-friendliness of the Pollensniffer was evaluated by a panel of volunteers in the northern part of the Netherlands. None of participants considered the Pollensniffer was complicated; 81% said it was easy to learn how to use the Pollensniffer and 50% indicated they would like to use the Pollensniffer more often. The major concerns on the Pollensniffer were related to the noise produced during operation (too much; 50% of participants), the size (too large; 14%) and the weight (too heavy; 28%).

3.2. Validation of the Pollensniffer in comparison to the static sampler

When the Pollensniffer PS1 was mounted on top of the rain cover of the static sampler, the number of pollen grains collected by the

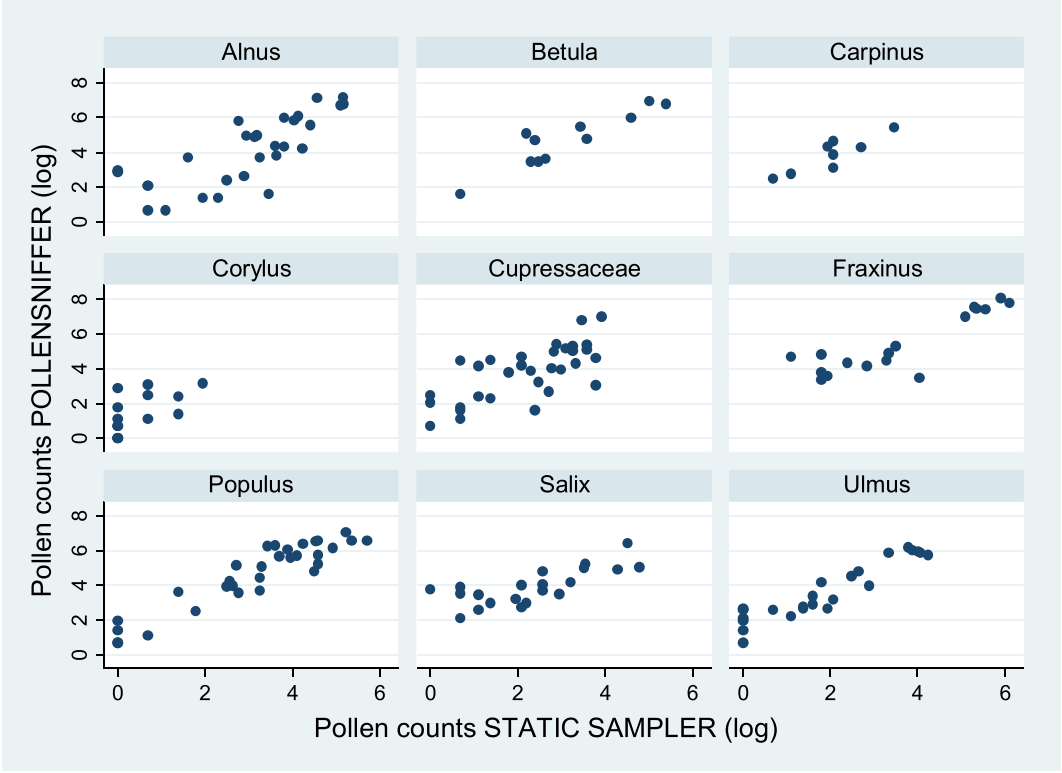


Fig. 3. Scatterplots of the pollen counts per hour of different pollen species from the static sampler and the Pollensniffer. For presentation purposes the counts were log transformed. In each plot Spearman's correlation coefficient (SCC) between the counts of different pollen types collected by the two samplers are shown. All correlation coefficients are significant ($p < .05$).

Pollensniffer and the static sampler correlated significantly for all pollen types analysed (Fig. 3). For most types the Spearman's correlation coefficient was strong (>0.8) but for Cupressaceae, *Salix* and *Corylus*, this was moderate (0.64–0.75). This experiment showed that for all types the Pollensniffer collected more pollen grains than the static sampler. To assess the magnitude of the difference between the two samplers, a regression analysis between the pollen counts by the Pollensniffer (PS) and by the static sampler (BU) was performed. This resulted in the equation: $PS = 5.766\ BU + 2.721$ ($R^2 = 0.788$). This regression equation indicates that the counts of the Pollensniffer are on average 5.8 times per hour higher than those in the static sampler.

Validation of the 5 individual Pollensniffers.

Five individual Pollensniffers (PS1-PS5) were placed on the same roof as the static sampler and were set up to collect eight 1 h-samples, each at the same time. The individual Pollensniffers (PS2-PS5) were compared to the validated Pollensniffer PS1. The Spearman's correlation coefficients between the pollen counts of the Pollensniffers PS2-PS5 and Pollensniffer PS1 were all significant ($p < .05$) and higher than 0.80. (Supplement Fig. S3). The percentage standard deviation of the mean values of the measurements with these five Pollensniffers varied between 9.3 and 27.4% resulting in a 15.5% average variability (Supplement Table S3). A one way analysis of variance (ANOVA) showed that the pollen collected by the different Pollensniffers did not significantly differ[$(F55,47) = 0.93$, $p = .601$)].

Grass and birch pollen collected at different locations.

At three locations in the city of Leiden pollen were collected for 15 min using the Pollensniffer in the morning, the early afternoon and the early evening. Concerning the variation in pollen counts (dynamics) during the day and the variation in number of pollen counts at large, similar results were observed for the three location on most days, although there are some notable differences. The peak values for birch pollen at the three locations were reached on the same monitoring day, but the number of pollen collected at these three locations varied notably on that day (Fig. 4a and b) i.e. in week 15, 2017 102 birch pollen grains (square rooted value [RV] 10.1) in Kweeklust, 28 pollen grains (RV 5.3) in the City Center and 39 pollen grains (RV 6.2) in Huigpark. In 2018, these values were much higher; e.g. on April 18th (week 16) 2338 pollen grains (RV 48.4) in Huigpark and 556 (RV 23.6) in Kweeklust and 312 (RV 17.6) in the City Center. This large difference in peak values between the years was also reflected in the annual pollen integral of the rooftop birch pollen, which amounted to 4398 pollen day/m^3 in 2018 compared to only 995 in 2017. Strikingly, in the City Center without any birch trees in the street or close by, the pollen counts were in the same range as collected in the parks, although as mentioned before, the highest numbers of pollen were collected in the parks.

Also for grass pollen (Fig. 4c and d) the levels were similar in the City Center to those in the parks although again the peak values were reached in the parks: 174 in 2017 in the Huigpark week 22 (June 2nd) and 209 in 2018 in Kweeklust week 23 (June 6th).

For grass pollen counts, the variations between the three locations were observed more frequently than for birch pollen; e.g. in 2017, week 22, a high number of grass pollen was collected in the Huigpark (174) in the morning with low numbers in Kweeklust (33). In the early evening it was the other way around: high numbers in Kweeklust (105) and low numbers in Huigpark (39). In contrast to birch pollen, peak values for grasses were not reached in the same week on the various locations: the Huigpark reached its peak value (178) in week 22 (June 1st) and Kweeklust (peak value 209) in week 23 (June 6th), which was 5 days apart.

During rain periods the number of birch or grass pollen that were collected at street level were usually low (see arrows in Fig. 4).

Comparison between street level and rooftop level pollen counts in time.

For a comparison between the rooftop level and street level pollen, we compared the daily pollen concentrations measured by the static sampler on the roof of the LUMC (as pollen/m^3) with the sum of the pollen collected at three 15-min periods of the day and from three locations in the city (sum of 9 measurements). Fig. 5 shows that the pollen counts at street level follow at large the rooftop level pollen concentrations: on days with high pollen concentrations measured at rooftop level also the street level pollen counts are high and vice versa. Nevertheless, exceptions can be found: e.g. April 12th 2017 (week 15) shows high street level birch pollen counts while the rooftop concentrations were low (Figs. 4a and 5a).

We studied the timing of the first pollen grains to be collected at rooftop level and street level for birch pollen and grass pollen. In 2017, this could not be studied for birch since the birch pollen season was already started before our series of measurements took off. In 2018, the first significant (≥ 4) number of birch pollen grains was collected on March 26th (19 birch pollen, see asterisk in Fig. 5b), while at rooftop the pollen concentration reached a significant level (≥4 pollen grains/m^3) on April 6th (6 pollen grains/m^3). So at street level birch pollen are detected 11 days earlier than on rooftop level (Fig. 5b).

For grass pollen at rooftop level (week 18) 7 pollen/m^3were recorded on April 30th 2017, while at street level 18 days earlier: 15 pollen were collected on April 12th (week 15) (see asterisk in Fig. 5c). In 2018, the first significant number of pollen were collected at rooftop level on May 2nd (4 pollen/ m^3, 24 h), while 19 days earlier (13th April, week 15) 5 pollen were collected at street level (see the asterisk in Fig. 5d). This indicates that birch pollen and grass pollen can be detected at street level 1 1/2 weeks and 2–3 weeks, respectively, earlier than at rooftop level.

4. Discussion

Here we describe the development and validation of a portable sampler, called Pollensniffer, which can be used to collect pollen in the direct environment of patients. In this study we have used the Pollensniffer to monitor grass and birch pollen grains present at street level in the city of Leiden and we show large differences in quantities between the three locations on different days and during the day. We also show that birch pollen and grass pollen are present 1 1/2–3 weeks earlier at street level (approximately 1 to 1.20 m) compared to rooftop level (22 m), which is the monitoring height for daily pollen monitoring with the static sampler.

First the Pollensniffer was validated in an experimental set up where the Pollensniffer was mounted on top of the rain cover of the static sampler. We showed that for most pollen types, the number collected by the Pollensniffer and the static sampler correlated significantly. The Pollensniffer appeared to be very efficient, since it collected on average 5.8 times more pollen per hour than the static sampler. An explanation for the high efficiency of the Pollensniffer compared to the static sampler might be found in the shape of the inlet. A pollen grain passing in an air streamline just above the inlet of the static sampler may not be drawn into the static sampler, while the wider conical inlet of the Pollensniffer may still collect this pollen grain.

Several devices for personalized allergen measurements have been described (Fiorina et al., 1997; Peel et al., 2014b; Renstrom et al., 2002; Werchan et al., 2018; Yamamoto et al., 2007) but the user-friendliness and the efficacy of these devices varies. Therefore, we developed the portable Pollensniffer in such a way that it can be carried, and, if required, can also be mounted onto the steering wheel of a bicycle, which will be described in another paper. Furthermore, the easily replaceable power bank generates a constant flow which can be maintained for 5–6 h. The measurements were performed with the inlet facing the current wind direction. This is a relevant instruction since this will help to generate a good flow into the sampler.

We asked 15 volunteers to evaluate our Pollensniffers, and the majority (81%) thought it was an easy-to-use device, which they would like to use more often (50%). The test panel suggested some improvements: (i) to reduce the noise during use (50%); (ii) to reduce the size

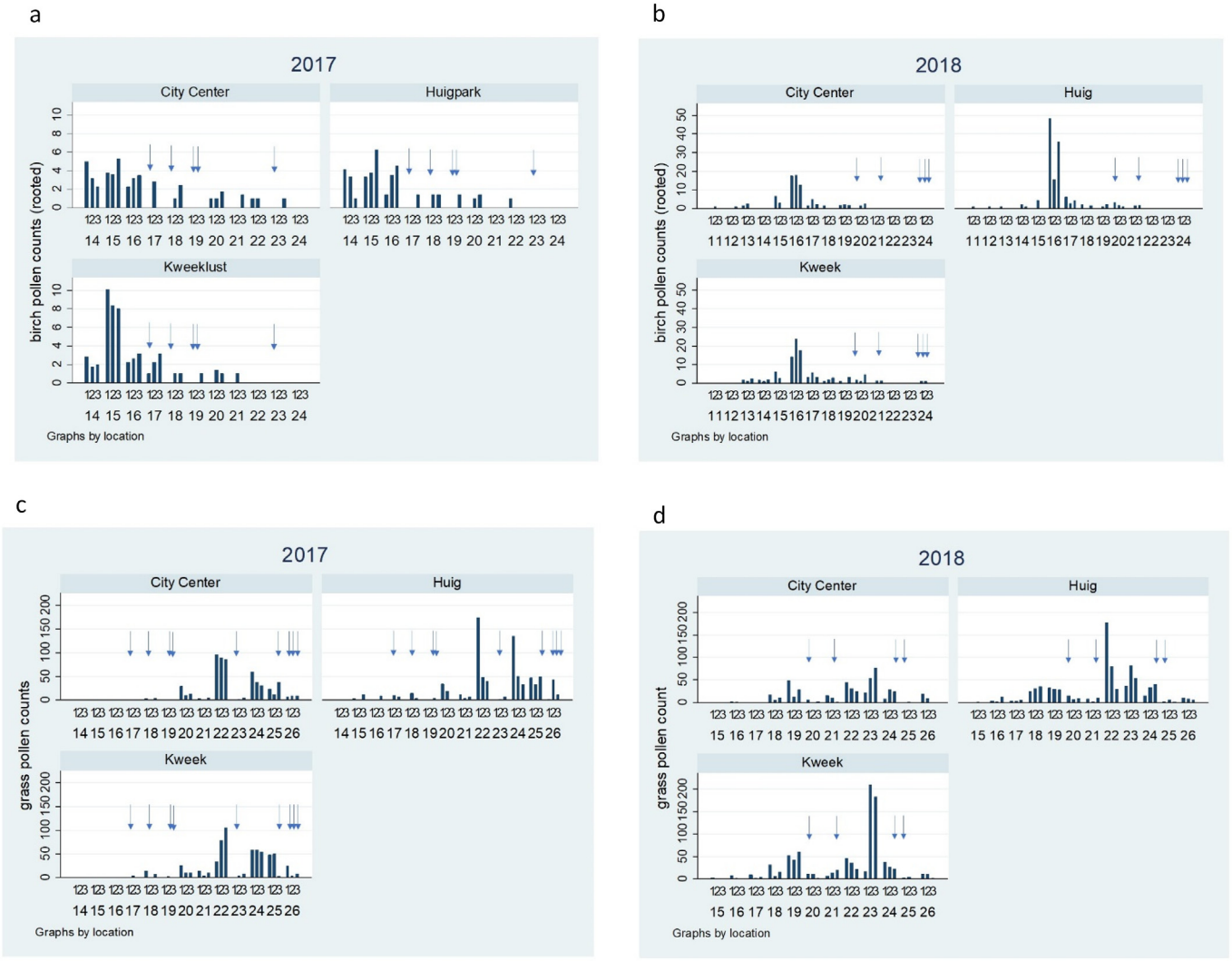


Fig. 4. Pollen counts in 2017 and 2018 at the different locations in the city of Leiden: City Center, Huigpark and Kweeklust. The numbers 123 indicate morning (1), early afternoon (2) and early evening (3). The numbers 14–26 indicate the week number of the measurement. Arrows indicate the incidence of rain during the pollen collection. For presentation purposes the birch pollen counts are rooted. Note that scale of the vertical axes is different. Figs. 4a and b represent birch pollen counts and Figs. 4c and d grass pollen.

(14%); and (iii) to reduce the weight (28%). These suggestions will be used when a next generation of Pollensniffers will be produced.

The pollen collected by the Pollensniffer and the static sampler at the same location correlate significantly and for most types the correlation is strong (SCC > 0.8). For *Corylus*, Cupressaceae and *Salix* this correlation was moderate (SCC = 0.64, 0.74, resp.). For *Corylus*, the pollen counts in the static sampler were very low (<0–7 pollen) (Fig. 3) which will affect the correlation. Molina et al. (Molina et al., 2010) found in a similar experiment also a low correlation for Cupressaceae pollen between a personal sampler and a continuous sampler (both from Burkard). The lower correlation for Cupressaceae and *Salix* might be caused by the fact that both these grains form clumps (Cupressaceae especially when they are broken) more often than other pollen types. These clumps may introduce a bias in the counts.

Comparison of five individual Pollensniffers shows that the number of pollen collected by the 5 devices are strongly correlated (Supplement Fig. S3). Furthermore, the average standard deviation between the measurements with the five Pollensniffers was 15.5%, which is comparable to the variation reported in 3 Hirst-type samplers placed 5 m apart, i.e. 20% of the pollen count (Buters et al., 2015). This shows that, although the measurements of the flow through the devices may slightly differ among the Pollensniffers, their performance in pollen collection is similar.

The first use of the Pollensniffers was to study the distribution of grass and birch pollen in the environment of the patients and we choose three locations at street level in the city of Leiden. One location in the shopping street (City Center), one in a park within the boundaries formed by the canals (Huigpark) and one more at the border of the city (Kweeklust). The total daily pollen counts for birch and grasses follow the pollen concentrations measured by the static sampler at rooftop level, although exceptions occur e.g. April 12th 2017 (week 15) with high pollen counts at street level and low pollen concentrations at rooftop level. Higher birch pollen counts at street level may be caused by the fact that in a 500 m circle around all three locations birch trees are present. When these trees are blooming their pollen may be dispersed better at street level and collected less at rooftop level.

The peak values for both birch and grass pollen were recorded in the parks, but on most days the pollen counts were in the same order of magnitude for the City Center and the parks, which may be striking for the City Center location since in this shopping street no grasses or birch trees were present. Only a few birch trees or well-maintained grass areas were present within a circle of 500 m. This indicates that birch and grass pollen can disperse very well within a city.

For birch trees, the temporal differences between the three locations are very similar, although the number of pollen collected at the various sites can differ markedly (Figs. 4a and b). The most striking differences

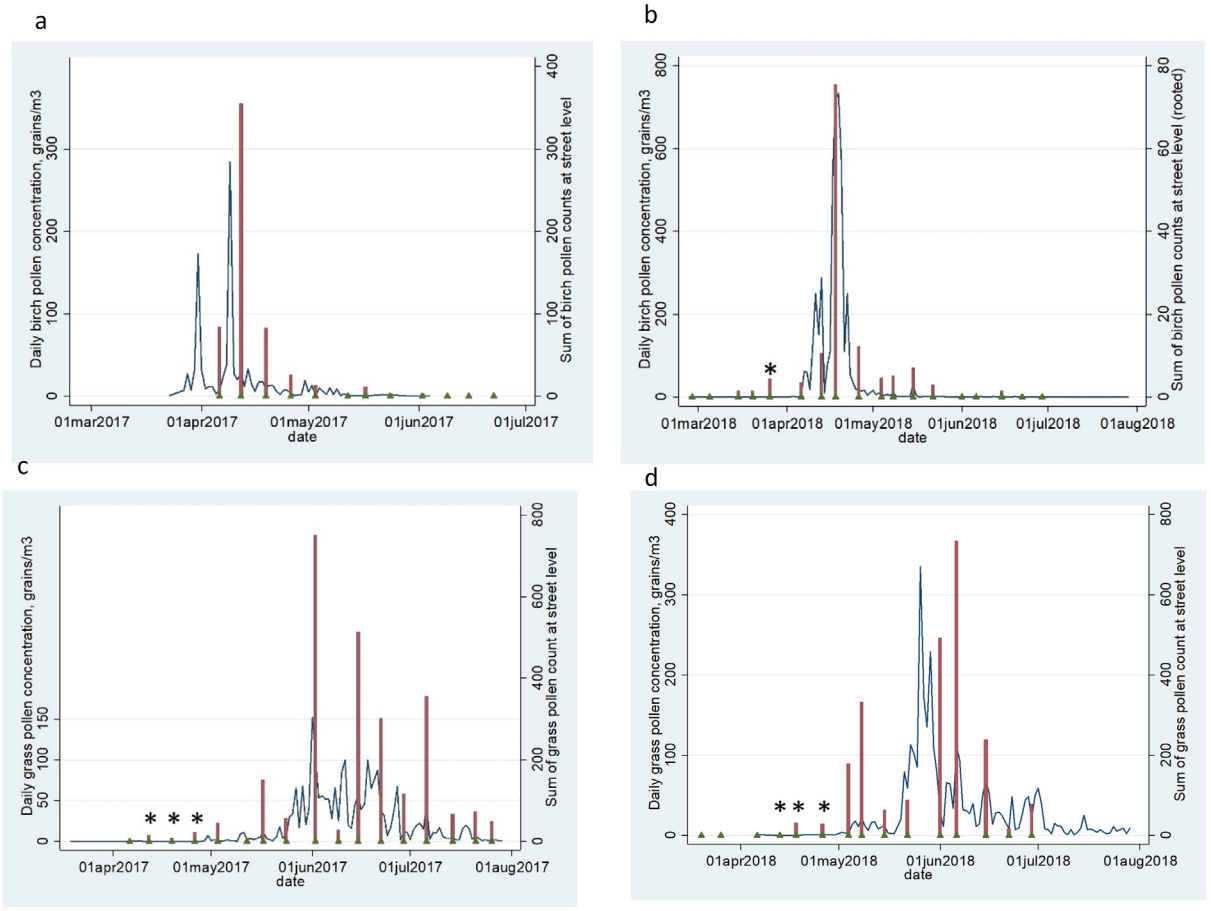


Fig. 5. At rooftop level daily pollen concentrations were monitored during the whole year (blue line). At street level the pollen were monitored once a week on variable days and they are shown as the sum of the collected pollen at the tree locations during the morning, early afternoon and early evening (red bars). Green triangles indicate the day at which a street level measurement was performed. Asterisks indicate days with more than 4 pollen collected at street level before pollen are detected at rooftop level by the static sampler. Figs. 5a and b represent birch pollen in 2017 and 2018 respectively. The street level counts of 2018 are rooted for presentation purposes. Figs. 5c and d represent grass pollen in 2017 and 2018 respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are found between the parks; there are days with very high pollen counts in one park and much lower pollen counts at the other 2 locations (Fig. 4a, week 15, 2017 and Fig. 4b, week 16, 2018). In 2017, highest values of birch pollen were collected in Kweeklust, while in 2018 the highest values were collected in Huigpark. This may be due to the fact that we only collected pollen one day in the week. Maybe in 2017, most birch trees in Kweeklust were ready to bloom on the collection day, while in 2018 the day of collection may have been the blooming day of most birches near Huigpark.

Also for grasses the temporal differences are similar for the different locations, although the three locations show more variation in time than the birch pollen. Pollen counts can be high in Kweeklust and low in Huigpark, but the other week it can be the other way around (Fig. 4d, week 22 and 23). Or pollen counts are increasing during the day in Kweeklust and decreasing in Huigpark during the day (e.g. Fig. 4c, week 22). These marked differences in pollen counts between the locations may be caused by the fact that different grass species are present near the Huigpark and Kweeklust, which may cause different dynamics in pollen production. Another explanation may be that the mowing regime differs among the different regions. Large differences in grass pollen distribution within a city has also been described by others (Hjort et al., 2016; Skjøth et al., 2013). The grass pollen will be produced by local urban sources, but since in the surroundings of Leiden also rural and recreation areas are present, it cannot be excluded that also these areas could be a source for the grass pollen detected in the city. However, several recent studies on street level measurements indicate that mainly local sources affect the pollen levels in the city domain and that during intense flowering the grass pollen level is a local scale phenomenon (Skjøth et al., 2013; Werchan et al., 2017).

These differences in pollen levels within a city may explain in part the diversity in symptom severity among allergic patients and it will hamper the development of accurate local pollen forecasts. It will be impossible with current techniques to take these local differences into account for pollen forecasts, but knowledge about the uneven dispersion of pollen in a city is relevant (Werchan et al., 2017).

The daily pollen monitoring takes place at rooftop level which is justified since the measurements should give an overview of the airborne pollen types within a larger area. These rooftop level measurements are used in most countries to inform the patients on the current pollen levels. We do not question the relevance of these data, however it is also important to know how these rooftop pollen concentrations relate to the pollen counts at street level. This study shows that at street level birch pollen was collected 1 1/2 week and grass pollen 2–3 weeks before those pollen types were collected at rooftop level.

In 1991, Rantio-Lethimäki was the first to describe that detection of grass pollen at street level occurs 2 weeks earlier than rooftop level (Rantio-Lehtimäki et al., 1991). Bastl et al. found a longer duration of the grass pollen season at street level compared to rooftop level (29 and 34 days in 2015 and 2016, respectively; (Bastl et al., 2019)). These results indicate that patients may be affected by the pollen before pollen are detected by the samplers at rooftop level. The pollen collected at the street level locations in the early season were quite low (see results),

but we have to realize that pollen were collected during only 15 min at each location. Nevertheless, patients for instance going by bike or on foot to work or doing exercise in the parks that stay out for a longer period, may inhale sufficient pollen to develop symptoms. Allergic patients report to their physician or allergist that they experience symptoms before the pollen are reported by the daily pollen concentrations (Pfaar et al., 2017)

5. Conclusions

A new portable pollen sampler, called Pollensniffer, has been developed, validated against the static pollen sampler and which is approximately 5–6 times more efficient in collecting pollen. This Pollensniffer has been used to monitor birch and grass pollen at street level. The pollen levels correlate well with the pollen levels at rooftop, but there can be large differences in pollen levels in a city between different locations and different 15-minute periods during the day. Furthermore, at the start of the birch and the grass pollen season, pollen were collected 1 1/2 to 2–3 weeks respectively earlier at street level compared to rooftop level, explaining why patients can have symptoms before the pollen season officially has started as defined by pollen counts in the rooftop sampler.

CRediT authorship contribution statement

Letty A. de Weger: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing.**Frank Molster:**Writing - review & editing, Conceptualization. **Kevin de Raat:**Investigation, Writing - review & editing.**Jeffrey den Haan:**Investigation, Writing - review & editing.**Johan Romein:**Writing - review & editing, Conceptualization. **Willem van Leeuwen:**Conceptualization, Supervision, Writing - review & editing.**Hans de Groot:**Conceptualization, Writing - review & editing.**Marijke Mostert:**Conceptualization, Supervision, Project administration, Writing - review & editing.**Pieter S. Hiemstra:**Conceptualization, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.140404.

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