Air quality using nose and mouth covering devices

A study by the Laboratory for air monitoring and radioprotection

Preparation of tests on nose and mouth covering devices (Photo: Appa Bolzano)

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SUMMARY

1. INTRODUCTION

For many years, the *Laboratory for air monitoring and radioprotection* has been carrying out measurements and assessments of air quality in indoor environments. These are closed spaces where people do not carry out industrial works. Schools are indoor environments where students and teachers remain many hours during the teaching activity. Consider that a student spends a considerable part of his time inside a classroom, more than 90% of his life is spent indoors. Well-being, comfort and health strongly depend on what a person breathes in an indoor environment. In the best conditions we breathe a gas mixture composed of 20.9% oxygen (O_2), 78% nitrogen (N_2), 0.04% (400 ppm) carbon dioxide (CO_2), 1% inert gas, and a variable rate of humidity (on average 6 g/m^3). With any physical or metabolic activity, we use part of oxygen, producing carbon dioxide and volatile organic compounds that we expel in the air. The more intense the activity we carry out, the greater is the amount of oxygen consumed and subsequently greater is the amount of carbon dioxide produced. The more time we spend inside a closed environment, the more people are present and the less the environment is ventilated, this gas mixture - called air - changes its composition for the worse much faster. In these cases, the amount of oxygen decreases, the amount of carbon dioxide and other substances such as volatile organic compounds and aerosols increases, making the indoor air quality no longer hygienically acceptable.
The recent health emergency caused by the spread of SARS-CoV-2 required us to cover our nose and mouth when people are in close vicinity for long periods. Many kinds of devices were suggested for this purpose, such as masks, neck warmers and shield visors, which modify the air quality that the person breathes and in many cases create discomfort. In particular, covering the nose and mouth implies that part of exhaled air is retained inside the device worn and then re-inhaled.
This study aims to characterize the quality of the air inhaled when a nose and mouth covering device is worn and to evaluate the discomfort. By covering the nose and mouth, a "micro" indoor environment is created and it is within this that we breathe.

2. REFERENCES

UNI EN 16798-1	Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.
ISO 17772-1	Indoor environmental input parameters for the design and assessment of energy performance of buildings.
UNI EN 14683:2019	Medical face masks - Requirements and test methods.
Ad-hoc AG IRK/AOLG, 2008	Leitfaden für die Innenraumhygiene in Schulgebäuden - Erarbeitet durch die Innenraumlufthygiene-Kommission des Umweltbundesamtes für die Innenraumhygiene in Schulgebäuden.

3. DEFINITIONS AND ABBREVIATIONS

PID	photoionization detector
TVOC	total volatile organic compounds
VOC	volatile organic compounds expressed per single component
CO_2	carbon dioxide
O_2	oxygen
N_2	nitrogen
ppm	part per million
Device	in this text: mask, visor, neck warmer worn to cover the nose and mouth
Exhalation	Breathing phase during which the air contained in the lungs is emitted outside through the respiratory tract
Inspiration	Physiological act that allows the penetration of air from the environment into the lungs
Inhaled CO_2 [ppm]	Concentration of CO_2 in ppm that a person enters into their respiratory system
CO_2 Re-inhaled [%]	Ratio, in percentage, between inhaled and exhaled CO_2
Test 1..n	tested person
Likert scale	technique used to measure attitudes and opinions through the administration of questionnaires.
Thermography	Measurement of the temperature distribution on the surface of a body obtained by identifying the emitted infrared radiations.

4. SCOPE

The objectives of the study are:

- Characterize the air quality inhaled by a person that wears a nose and mouth covering device in different conditions.
- Check emissions of harmful substances from device material that can be inhaled by the wearer.
- Assess the discomfort due to prolonged usage of the devices.

The study **<u>does not address the following aspects</u>**:

- The efficiency of a nose and mouth covering device with respect to preventing the transmission of viruses.
- Toxicological and health effects related to exposure to pollutants.
- Quality of the inhaled air, using a device, under intense acitivities.

5. MODELS USED AND MEASUREMENT METHODS

5.1 Parameters and indicators

The principal components of the air inhaled and exhaled by a person are oxygen (O_2), carbon dioxide (CO_2), nitrogen (N_2), volatile organic compounds (VOC), biological agents and water vapor. Similar to the assessments of indoor air quality, CO_2 is used as the principal indicator for the tests reported in this study. CO_2 concentration can be measured with precision and its dilution in the air is also representative for any other compounds inhaled/exhaled. Measurements of O_2 and TVOC were also carried out during the tests, however, the data elaborations reported in this study refer exclusively to CO_2.

5.2 Inspired air

Sampling and measurement method used for the tests have two requirements:

1. To not interfere with breathing, that is, the analyzed air must be representative of what person actually inhaled.
2. Separate the air that enter the lungs (inhaled) from the air coming out (exhaled).

Measurement technique: at each respiratory act and during the entire inspiration phase a small amount of air is picked up through a probe placed between the nose and mouth and is collected in a Tedlar bag (PVDF) until full. The passage of air from the probe to the bag is managed by a pump that is activated only during the inhalation phase, whereas during exhalation, the pump is turned off and a valve inhibits any entry of air into the pump and therefore into the bag. The pump and valve are activated manually by the person carrying out the test, following their breathing pattern. The contents of the bag were then analyzed.

Figure 1

Figure 2

Figure 3

Figure 4

Sampling process:

- a silicone tube with holes with a diameter of 4mm (internal) that wraps the head between the nose-mouth and the nape;
- a PTFE pump regulated at a flow rate of approximately 1.4 L/min;
- a valve that stop the air entering the pump during exhalation;
- an activation command (pump and valve) which is managed by the person carrying out the test:

1. Inspiration: pump on and valve open.
2. Expiration: pump off and valve closed.

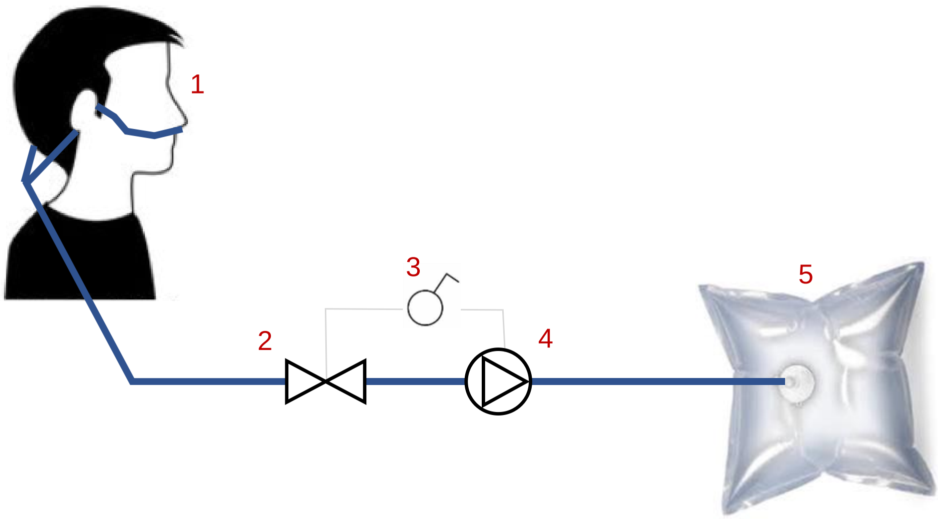

Figure 5. Sampling process

Sampling process is reported in Figure 5:
1 perforated silicone tube that wraps the head between the nose and mouth
2 valve
3 switch (manual operation)
4 pump
5 Tedlar bag.

Note:
- *Flow (1.4 L/min) is mantained low enough in order to not interfere with the pressure conditions present between the nose and mouth and with the device during the inspiration phase.*
- *Separate Tedlar bags of 5L and 10L were used to contain inhaled and exhaled.*
- *PTFE and silicone tubes were used to connect the various components of the sampling process.*
- *The internal volume of the tubes from the probe to the valve was approximately 0.025L.*
- *The duration of inspiration varied between 4 and 15 seconds.*
- *The air volumes of a single inspiration varied from 0.8L to 2.5L*
- *Duration of inspiration and volume of air inspired are not related, i.e. a short inspiration does not necessarily correspond to a smaller volume of air, because the person may have inspired for less time but with more force.*
- *The volume taken from the pump during the inspiration phase depended on how long it remained active. The volumes therefore varied between 0.09L and 0.35L*
- *The time that air moves from the sampling point to the valve was <1 second.*

Tests were performed on these devices:

1. FFP2/KN95 mask
2. Surgical mask
3. Handcrafted mask
4. Screen/Visor
5. Neck warmer

Conditions of using the devices:
Preliminary tests
1. Sitting, without the device
2. Sitting, without the device with air speed of 0.5-1.0 m/s near the face (to simulate the effect of the wind or movement)
3. Sitting, with the device with air speed of 0.5-1.0 m/s near the face (to simulate the effect of the wind or movement).

Tests
4. Sitting with the device
5. Step: Light effort of stepping up/down with the device worn[a]

[a] stepping up/down was chosen in order to make uniform light effort for everyone. The test consisted of going up and down from the step at a slow pace.

5.3 Exhaled air

The exhaled air was collected in a Tedlar bag by exhaling inside an airtight mask connected to the bag by a silicone tube. The contents of the bag were than analyzed, in order to measure oxygen and carbon dioxide concentration.

5.4 Thermographic measurements

Using a thermographic camera, the surface temperatures of the face (with and without device) were measured at the beginning and the end of each test. The variation in surface temperature is an indicator of perceived discomfort.

5.5 Subjective analysis

Short questionnaires were distributed to the test persons (in Tables and diagrams - called Test 1 through n, n = 8) to describe their impressions and perceptions.

5.6 Device analysis

Concentrations of pollutants were analyzed for the devices (formaldehyde and VOC).

5.7 Instrumentation

Table describes the instrumentation used for the analyzes.

Parameter	Measurement technique	Instruments
O_2	paramagnetism	HORIBA PG250
CO_2	non-dispersive infrared	
TVOC	photoionizer	ION TIGER
VOC	gas chromatography	HP 5973
Surface temperature	infrared	FLIR E6

6. RESULTS

The tests were performed from June to August 2020, in the Laboratory Library. The windows were kept open during measurements in order to maintain the indoor CO_2 concentration around 450 ppm. The concentration was constantly monitored, with temperature, humidity and air velocity.
8 adults were selected, differing in age, sex, physical condition and respiratory characteristics. Each person repeated the test three times for all types of devices and in the two conditions of use. In total, 350 tests were performed with and without devices, as well as 105 thermographic photos.

6.1 Respiratory acts, volumes and exhaled composition

Table 1 report respiratory acts, air volumes and composition of the breath. Table 2 report the minimum, average and maximum values. Same results are represented in Figure 6.

Table 1. Breathing rate, volume and air concentrations (Test n)

		Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
breathing rate	nr/min	16,7	6,0	3,3	9,3	5,3	10,8	7,0	11,3
exhaled air volume in one minute	L	20,5	7,6	4,9	7,5	8,3	17,1	18,3	8,9
exhaled air volume per breath	L	1,2	1,3	1,4	0,8	1,6	1,6	2,6	0,8
O_2	Vol%	16,1	16,6	17,4	18,2	15,5	18,4	18,7	17,6
CO_2	ppm	43000	43000	38000	34000	48400	32000	27600	39200

Table 2. Exhaled air: oxygen and CO_2 concentration

exhaled air	unit	Minimum value	Mean value	Maximum value
O_2	Vol%	15,5	17,3	18,7
CO_2	ppm	27600	38130	48400

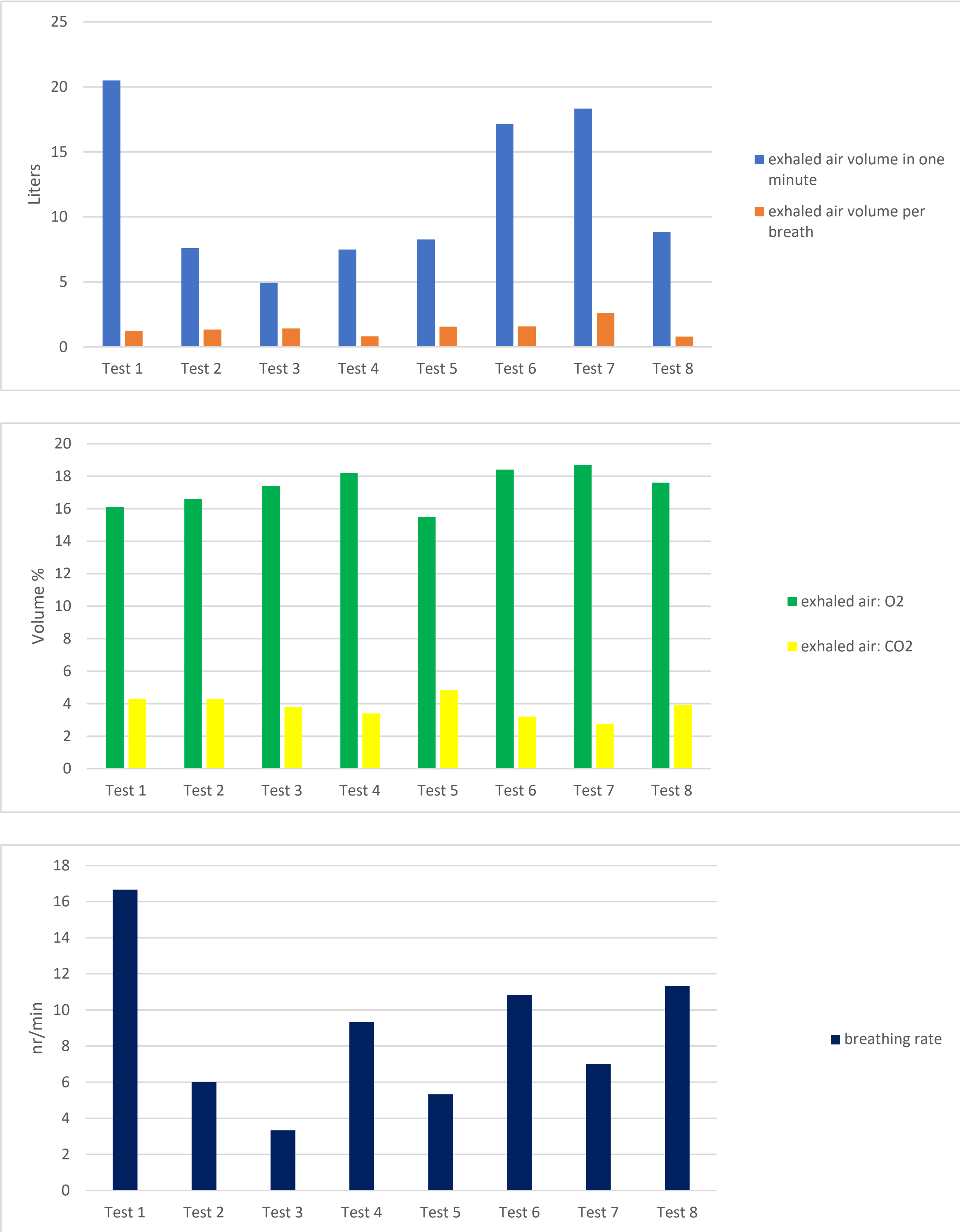
25
20
15
10
5
0
Liters
Test 1
Test 2
Test 3
Test 4
Test 5
Test 6
Test 7
Test 8
exhaled air volume in one minute
exhaled air volume per breath
20
18
16
14
12
10
8
6
4
2
0
Volume %
exhaled air: O2
exhaled air: CO2
18
16
14
12
10
8
6
4
2
0
nr/min
breathing rate

Figure 6

Figure 7 shows the CO_2 concentration of exhaled air measured.

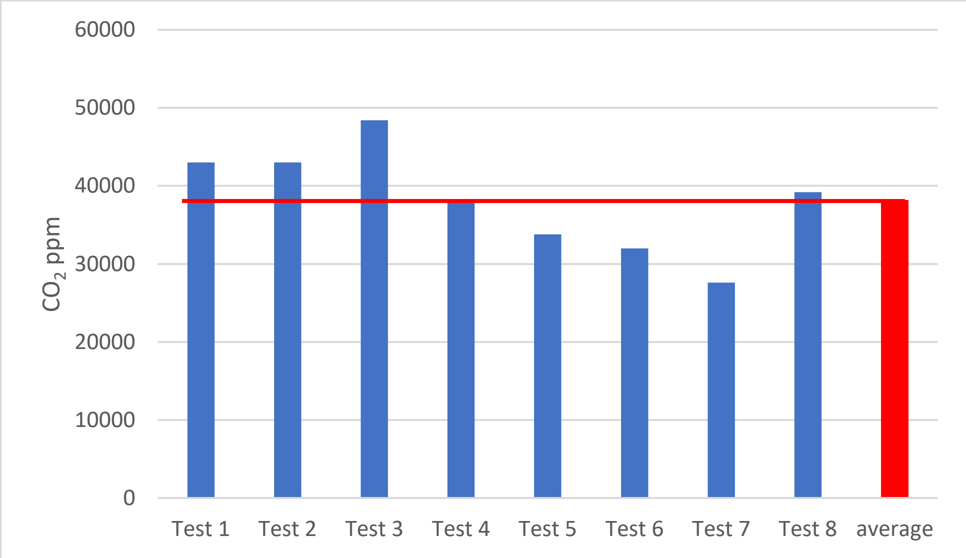

Figure 7. exhaled air: CO_2 concentration (ppm)

Note:

During the tests, in the two conditions, the person could breathe in their usual way. Even though the person was not asked to keep under control, in order to stay as close as possible to the real conditions of use of the device, we still observed some variables that significantly influenced the result:
- breathing frequency
- head tilt
- adhesion of the device to the face
- air velocity near the nose-mouth, even with the device.
The effect and presence of these elements that are difficult to control also allow us to have see the variability of real scenarios.

6.2 Influence of air velocity

The test was performed in two conditions:

1. Sitting - still air
2. Sitting - air velocity of 0.5-1.0 m/s on the face (Figure 3).

It was observed that both with and without the device, with a slight movement of air (0.5-1.0 m/s equal to a slow walk, in the case of the full-face helmet the speed was 10 m/s) CO_2 concentration measured is significantly lower than when the air is still.

The tests carried out on the manikin (Figure 8 and Figure 9) explain the main reason for these values. In still air conditions, the exhaled air partially returns to the face and then it is re-inhaled. In moving air conditions, the exhaled air is quickly removed from the face, even with the device on. To have a further example of the role of air speed on the device, a test was also carried out with a full-face helmet.

Figure 8. Mannequin exhalation, still air.

Figure 9. Mannequin inhalation, still air.

Figure 10. Influence of air velocity without the device

Figure 10 represents the concentration of CO_2 (inhaled air) without the devices, in a sitting position and still air (in blue) and in a sitting position with air movement (with a speed between 0.5 and 1.0 m/s - in orange in the graph). Test 1 - 8 are the eight tested people. The variability of the results depends on the different breathing modes of people, who under the same conditions exhale and inhale air in different ways. The concentrations with air movement are lower for all eight people as compared to the case of absence of air movement.

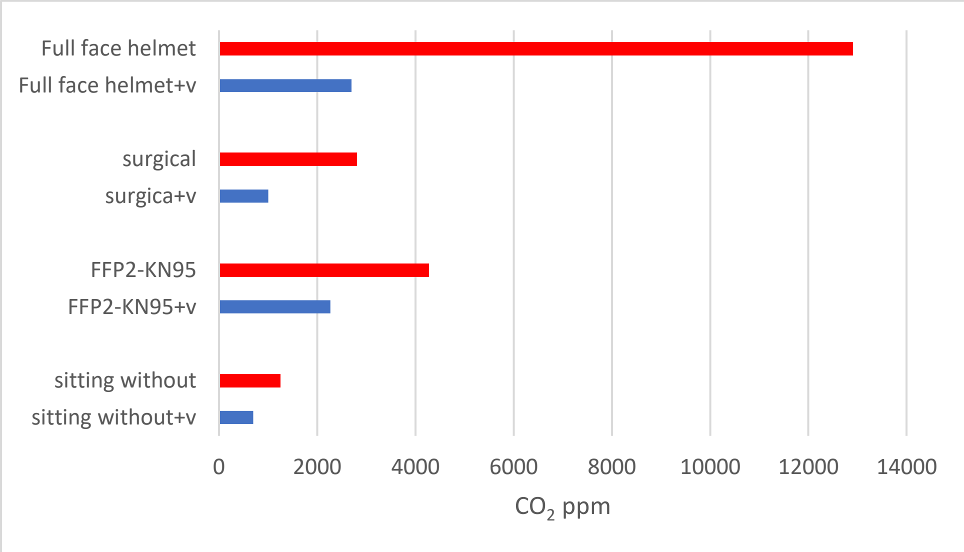

Figure 11. Influence of air velocity with device

Figure 11 shows CO_2 concentration (inhaled air) with devices: in red in conditions of still air, in blue with air moving with a speed between 0.5 and 1.0 m/s (for the helmet the speed was on average 10 m/s). Similar to the tests without the devices, the concentrations with air movement are lower than the case of absence of air movement.

6.3 Measurements with and without devices

The results of the tests with the devices are represented below. When the CO_2 concentration is measured in the re-inhaled air, the "net" contribution was estimated by subtracting the ambient concentration of 450 ppm from the absolute concentration measured by the instrument. This is henceforth specified as the "net CO_2 concentration" in this report. Each graph shows the minimum, average and maximum net CO_2 concentration of the series of measurements.

Sitting and step: CO_2 concentration

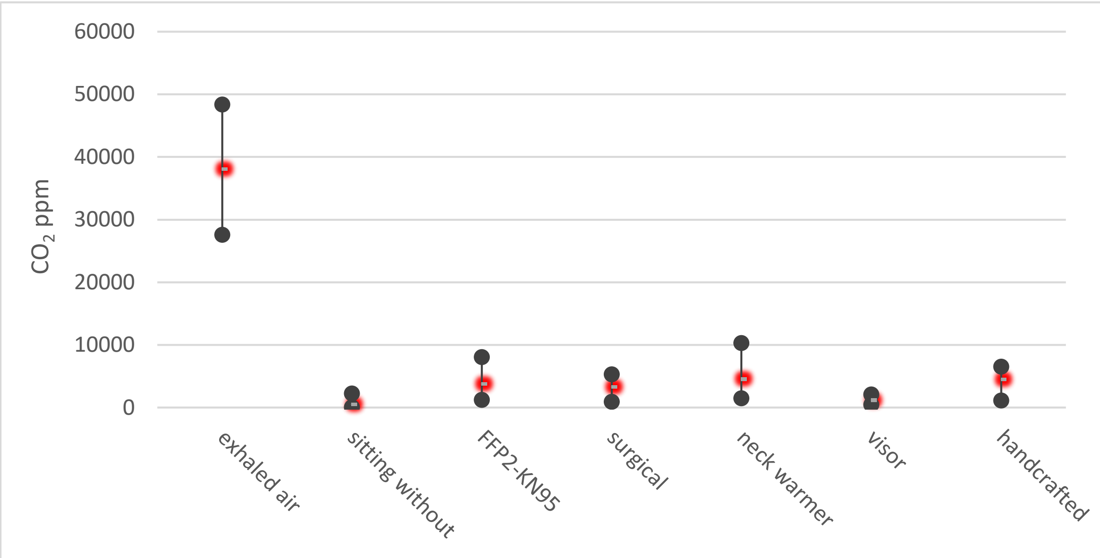

Figure 12. Sitting. Inspired CO_2 Concentration net of ambient CO_2

Figure 12 shows the results of the CO_2 concentration measurements in ppm for the inhaled air net of that of the environment during the seated tests.

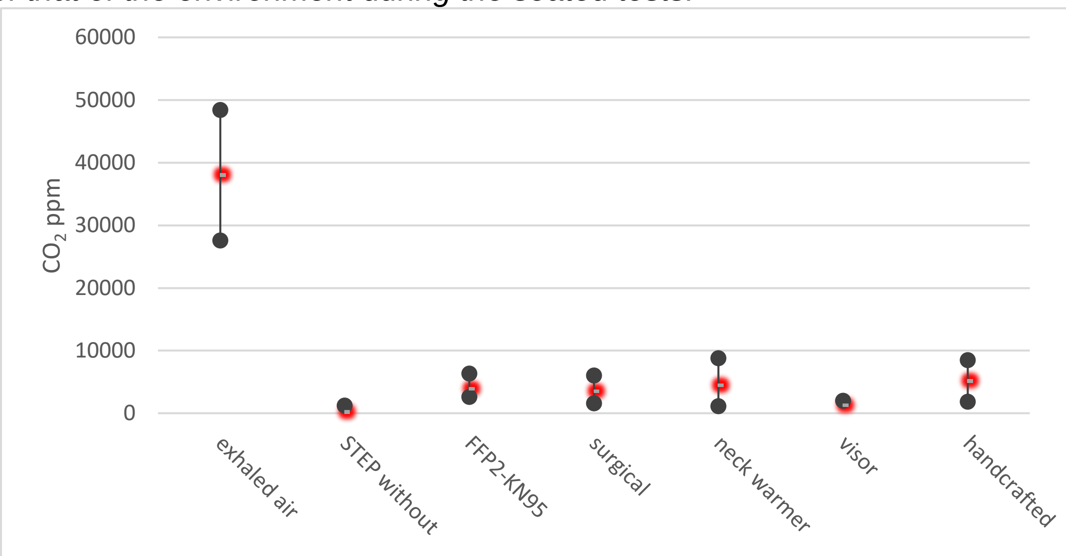

Figure 13. Step. Inspired CO_2 Concentration net of ambient CO_2

Figure 13 shows the results of the CO_2 concentration measurements in ppm for the inhaled air net of that of the environment during the step tests.

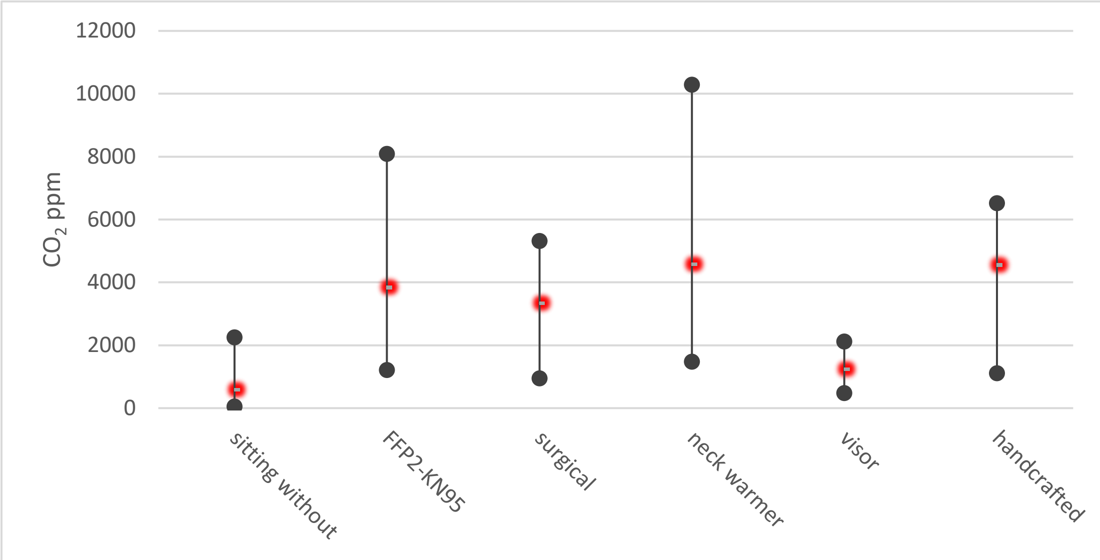

Figure 14. Sitting. Inspired CO_2 Concentration net of ambient CO_2

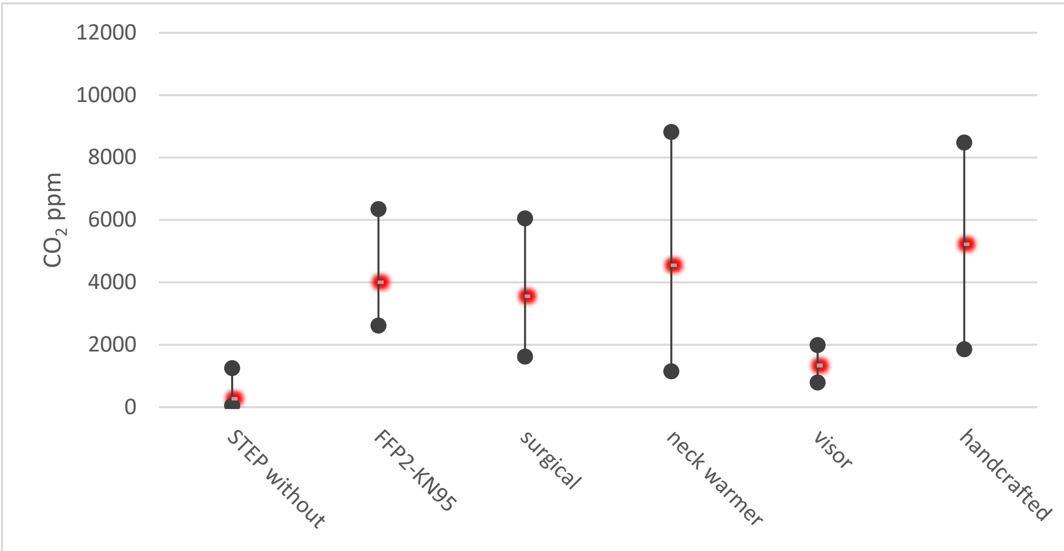

Figure 15. Step. Inspired CO_2 Concentration net of ambient CO_2

Figures 14 and 15 show the same data as in Figures 12 and 13 without exhaled air.

Percentage of re-inhaled CO_2 in seated and step conditions

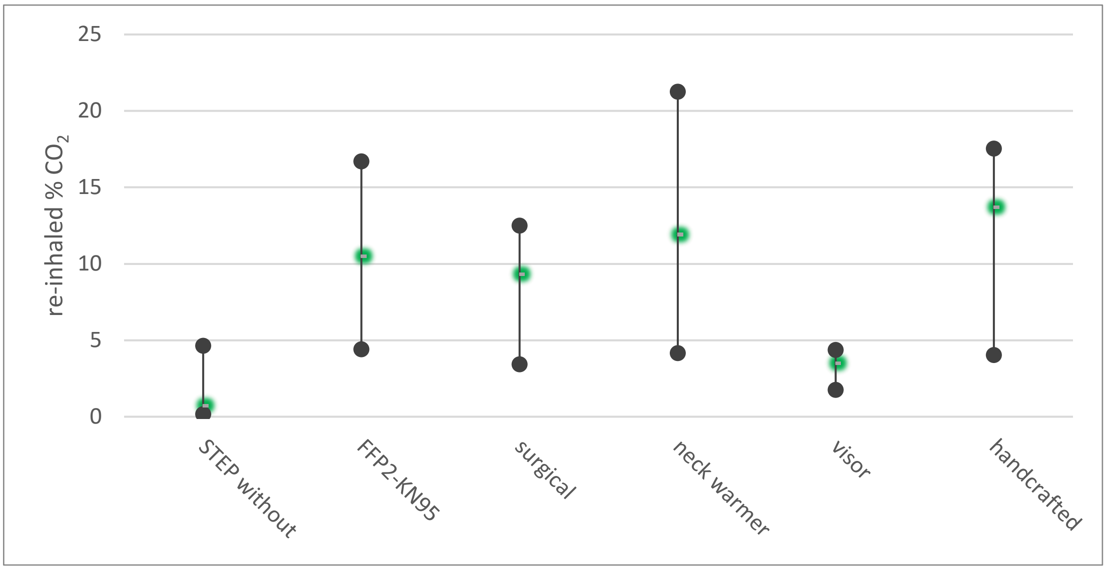

Figure 16. Sitting. Net re-inhaled CO_2 concentration

Figure 16 shows the ratio, in percentage, between the inspired and expired CO_2 in the seated tests. This is called re-inhaled CO_2.

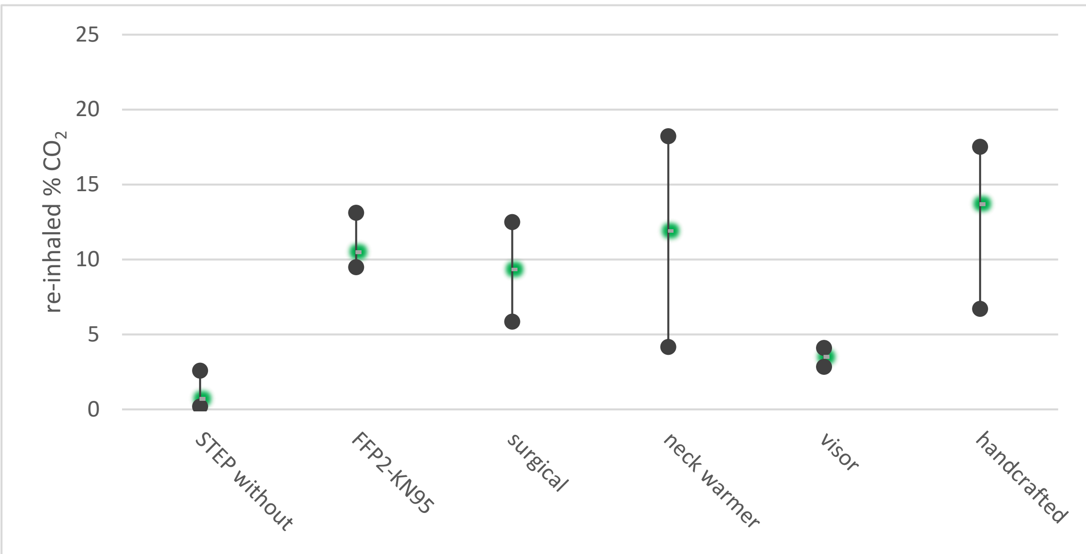

Figure 17. Step. Net re-inhaled CO_2 concentration

Figure 17 shows the ratio, in percentage, between the inspired and expired CO_2 in the step tests. This is called re-inhaled CO_2.

Table 3. Inspired CO_2 concentration net of ambient CO_2

			Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	mean value
sitting	without	CO_2 ppm	700	450	250	350	150	2250	550	50	590
	FFP2-KN95	CO_2 ppm	4140	2520	2450	1220	2380	8080	5350	4650	3850
	surgical	CO_2 ppm	3760	980	2320	950	4020	4880	4580	5320	3350
	neck warmer	CO_2 ppm	5730	3320	4920	3080	2080	5800	10280	1480	4590
	visor	CO_2 ppm	1310	480	2120	480	1620	950	1450	1520	1240
	handcrafted	CO_2 ppm	4830	1180	5920	1120	4850	5850	6520	6280	4570
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	mean value
step	without	CO_2 ppm	280	50	50	350	50	1250	150	50	280
	FFP2-KN95	CO_2 ppm	4890	2620	3780	3050	2750	3380	6350	5250	4010
	surgical	CO_2 ppm	4820	1620	3520	1620	2850	3220	6050	4850	3570
	neck warmer	CO_2 ppm	6140	3350	3920	3850	1150	6140	8820	3020	4550
	visor	CO_2 ppm	1360	780	1050	780	1620	1720	1980	1450	1340
	handcrafted	CO_2 ppm	6130	1850	4650	3850	3580	6150	8480	7150	5230

Table 4. Percentage of re-inhaled CO_2 compared to exhaled

		min	mean	max
sitting	without	0,2%	1,6%	4,6%
	FFP2-KN95	4,4%	10,1%	16,7%
	surgical	3,4%	8,8%	11,0%
	neck warmer	5,4%	12,0%	21,2%
	visor	1,8%	3,3%	4,4%
	handcrafted	4,0%	12,0%	13,5%
		min	mean	max
step	without	0,2%	0,7%	2,6%
	FFP2-KN95	9,5%	10,5%	13,1%
	surgical	5,9%	9,4%	12,5%
	neck warmer	4,2%	11,9%	18,2%
	visor	2,8%	3,5%	4,1%
	handcrafted	6,7%	13,7%	17,5%

The percentages reported in Table 4 represents the re-inhaled part with respect to the exhaled air. These results are shown in the graph of Figure 18. For example, for the FFP2-KN95 devices, an average value of re-inhaled CO_2 of 10.1% in the seated case and 10.5% in the tests with the step was measured.

Comparison of devices in seated and step conditions

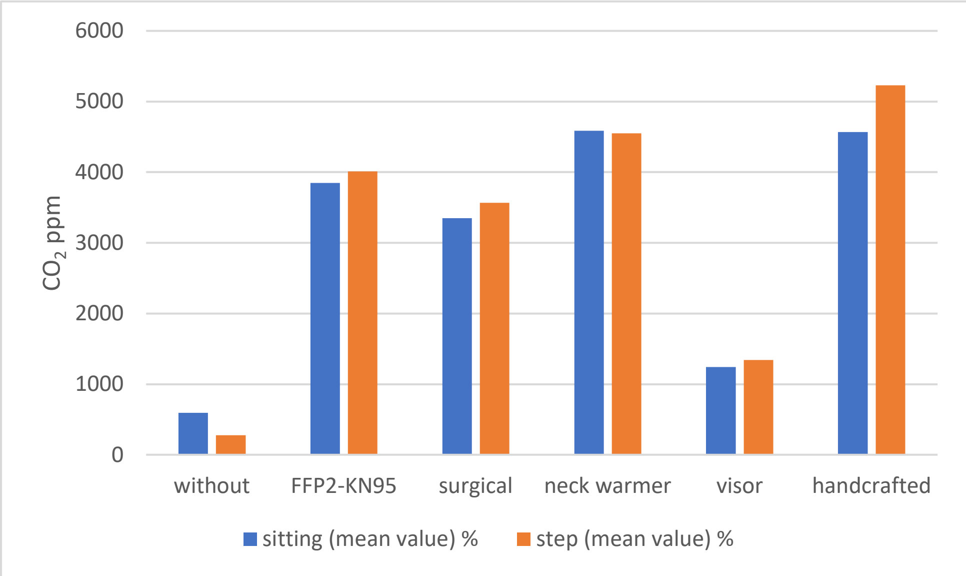

Figure 18. Inspired CO_2 Concentration net of ambient CO_2. Mean values

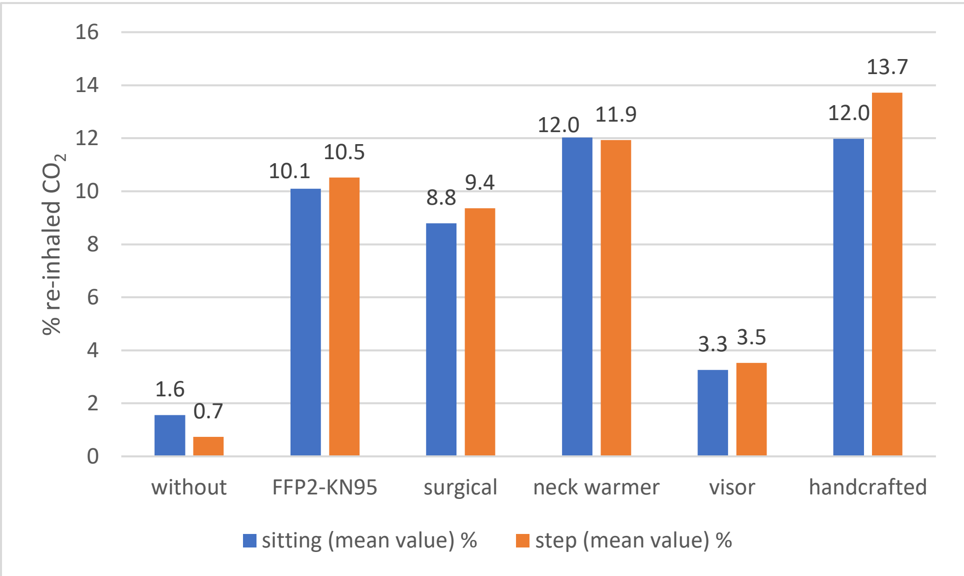

Figure 19. Net re-inhaled CO_2 concentration. Mean values

Figures 18 and 19 show the average values of CO_2 concentrations of inspired and re-inhaled for the various devices analyzed, respectively for the seated and step tests.

Tables 5 and 6 shows a comparison of the CO_2 concentrations in everyday situations and the relative guide values.

Table 5. CO_2 concentrations for comparison: guide value (first line) and typical concentrations (APPA Bolzano)

Guide value for indoor environments	CO_2 ppm	1000
School classroom	CO_2 ppm	800-6000
Single bedroom - doors and windows closed	CO_2 ppm	800-3000
Train	CO_2 ppm	1500-2500
Bus	CO_2 ppm	1000-2000
Car (1 person)	CO_2 ppm	1000
Pizzeria-restaurant	CO_2 ppm	800-2000

Table 6. Indoor CO_2 concentration values in Ad-hoc AG IRK/AOLG, 2008

CO_2 concentration (ppm)	Hygienic evaluation	Advice
< 1000	Hygienically not relevant	• No intervention
1000-2000	Hygienically relevant	• increase air changes • Check and improve ventilation habits
>2000	Hygienically unacceptable	• Check the ventilation system of the room • Check for further ventilation improvements

Note: various ISO-EN standards report reference values for CO_2 in indoor environments, in particular UNI EN 16798-1 and ISO 17772-1 are specific for the design of ventilation systems and are used in public buildings. For the purposes of this study we prefer to report the guiding values proposed by the German Ministry of the Environment Ad-hoc AG IRK/AOLG, 2008", which are more easily understood, as these are very similar to the ISO-EN standards.

Comments to the measurements

Tests show that CO_2 concentration of re-inhaled air varies considerably for different nose and mouth covering devices. The highest values were obtained with FFP2/KN95, neck warmer and handcrafted mask. Slightly lower are the values of the surgical mask while with the visor, CO_2 concentration is just above what is breathed without wearing any device. The differences in concentration between the minimum and maximum values are mainly due to the person's respiratory rate, the inclination of the head, the adhesion of the device to the face and the speed of the air near the nose-mouth. There are no significant differences between the two conditions examined: sitting and step; this is because the greater production of CO_2 under stress is balanced by the greater energy with which it is expelled and the slight movement of air that is created by going up and down the step. Under intense exertion, gas concentrations and breathing conditions would certainly change, but this scenario is out of the scope of this study.

The percentage of re-inhaled CO_2 varies from a minimum value of 3.3% obtained with the visor to a maximum of 13.7% obtained with the handmade mask (Figure 19). The remaining inhaled air obviously comes from the environment. The measurements were made in an environment with low CO_2 concentration (about 450 ppm). This value in the data analysis was subtracted from the inspired CO_2. In fact, in a real situation, the concentration of the environment must be added to the re-inhaled concentration, which is often much greater than 450 ppm. It is also observed that even without wearing a device, in a sitting condition, with still air, tested people re-inhaled 1.6% of their CO_2 while on the step, therefore under light effort and movement of air, the value was 0.7%.

CO_2 concentration in the breath varies from a minimum of 1240 ppm measured with the visor to a maximum of 5230 ppm measured with the handmade mask. In this regard it must be underline what the guidelines of the German environment ministry report (Ad-hoc AG IRK / AOLG, 2008): for indoor environment CO_2 concentration in the range 1000-2000 ppm it is necessary to increase the ventilation of the environment, while above 2000 ppm it is not hygienically acceptable, and an intervention is necessary to improve indoor air. Comparing the IRK guide values with the results of the tests, it appears that only with the visor worn the CO_2 breathed can remain below 2000 ppm, while with the other devices the air breathed would not be hygienically acceptable. Observing Table 5, however, it appears that in various conditions of daily life, in indoor environments, the value of 1000 ppm is exceeded for long periods. In particular, inside the classrooms, where students and teachers stay for most of the day, CO_2 over 1000 ppm of are often exceeded, reaching values even higher than 5000 ppm.

The results obtained demonstrate the importance that the environment, inside which the mask must be worn, should have optimal ventilation characteristics, so that the CO_2 concentration is kept below 1000 ppm. This is a requirement that must be pursued even in the absence of the devices, but becomes more important when such devices are used.

6.4 Face surface temperature analysis

The results of the surface temperature measured with an infrared camera are represented below.

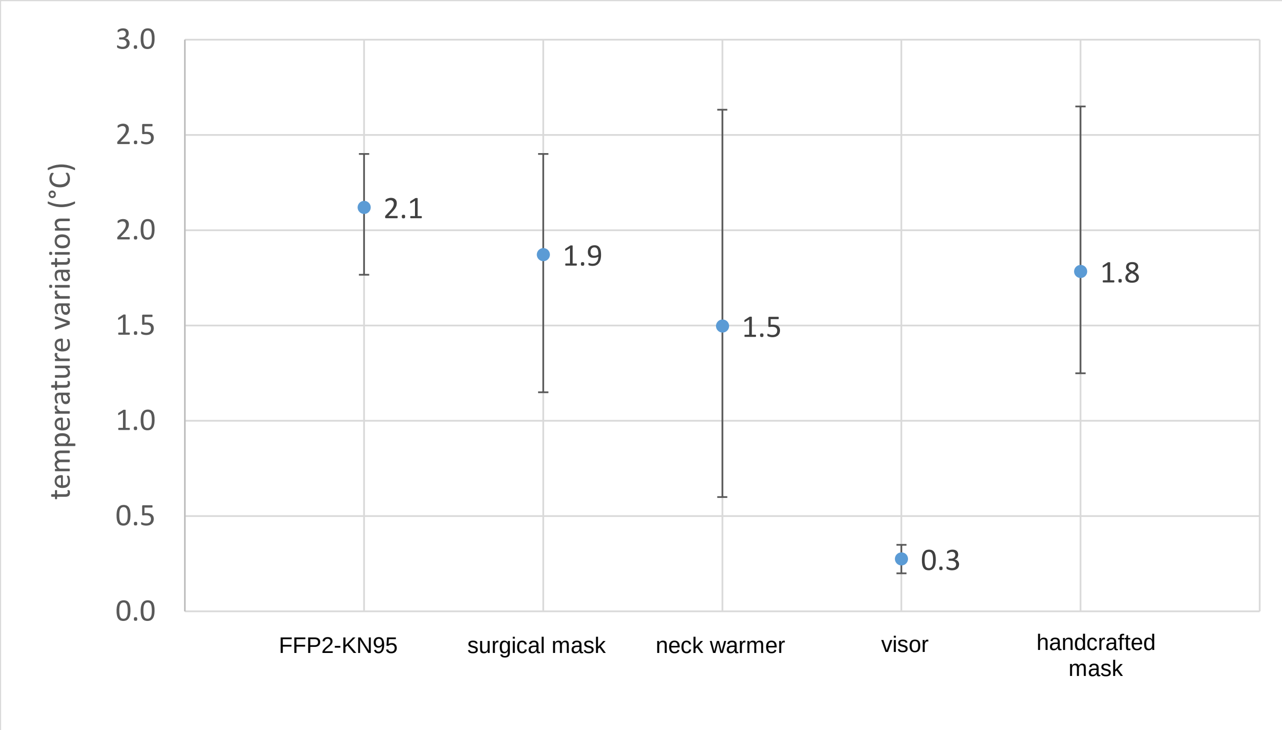

Figure 20. Variation of face surface temperature

Figure 21

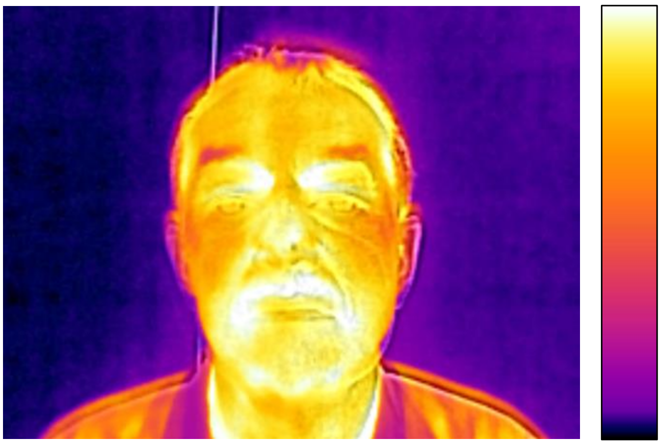

Figure 22

Figure 20 shows the minimum, average (in blue) and maximum (extremes of black bars) values of the temperature variations for each device. Measurements were carried out in seated and step positions and were then averaged for all eight test subjects.
The two thermal images were both taken without the device, Figure 21 before wearing it and Figure 22 after wearing it. The lighter the color, the higher the surface temperature. Figure 22 shows that the area covered by the device is the hottest.

The thermographic analysis (Figure 21 and Figure 22) shows that, in the portion of the face covered by the device, the surface temperature of the skin is 1.5-2.1 degrees higher than the portion of the face not covered; this data does not refer to the visor, in which there is an average temperature variation of 0.3°C only. For neck warmers, the temperature increase is not concentrated in the mouth-nose area, but extends to all the area covered by the device.
The difference in temperature causes a slight sweating. Temperature variations and sweating are immediately perceived with discomfort by the person wearing the device. Under more intense efforts the temperature difference between the covered and uncovered parts is greater with a consequent increase in perceived discomfort. The subjective analyzes reported in paragraph 6.6 confirms the face surface temperature analysis.

6.5 Moisture absorbed by the device

The test was performed by wearing the device continuously for 1.5 hours, with various activities, sitting and in light movement. Every 30 minutes the weight of the device was recorded and the variation due to the possible absorption of moisture emitted by the person was evaluated.

	unit	Start	30 min	60 min	90 min
KN95	g	5,34	5,35	5,34	5,34
surgical	g	3,11	3,12	3,12	3,00
neck warmer	g	27,81	27,93	28,84	27,87
handcrafted	g	18,96	19,00	19,01	18,84

Tested devices have minimal weight variations, the damp sensation perceived by the person is almost exclusively caused by sweating of the part of the face covered by the device.

6.6 Subjective analysis

Subjective analysis performed on all the people who participated was aimed to evaluate, using a 5-point judgment scale (Likert scale), the comfort, difficulty in breathing and speaking and any psychological effects induced by the use of devices. The 5 questions were the following:

- it is uncomfortable
- it makes me lose breath
- it makes me claustrophobic
- it makes me dizzy
- It is difficult to speak.

The results showed a considerable variability of responses for all devices with the exception of screens. In addition, there is a marked dissatisfaction in the use of neck warmers, probably partly linked to the summer season and the temperatures during the tests.
Figure 23 shows the questionnaire. The rating scale ranged from 1 to 5: the higher the value, the higher the discomfort.

Date, time	Type	Person	Note
	☐ FFP2-KN95 ☐ surgical mask ☐ neck warmer ☐ visor ☐ handcrafted mask	M/W	

	Never	little	yes	very	Very much
	1	2	3	4	5
it is uncomfortable					
it makes me lose breath					
it makes me claustrophobic					
it makes me dizzy					
It is difficult to speak					

Figure 23. Questionnaire

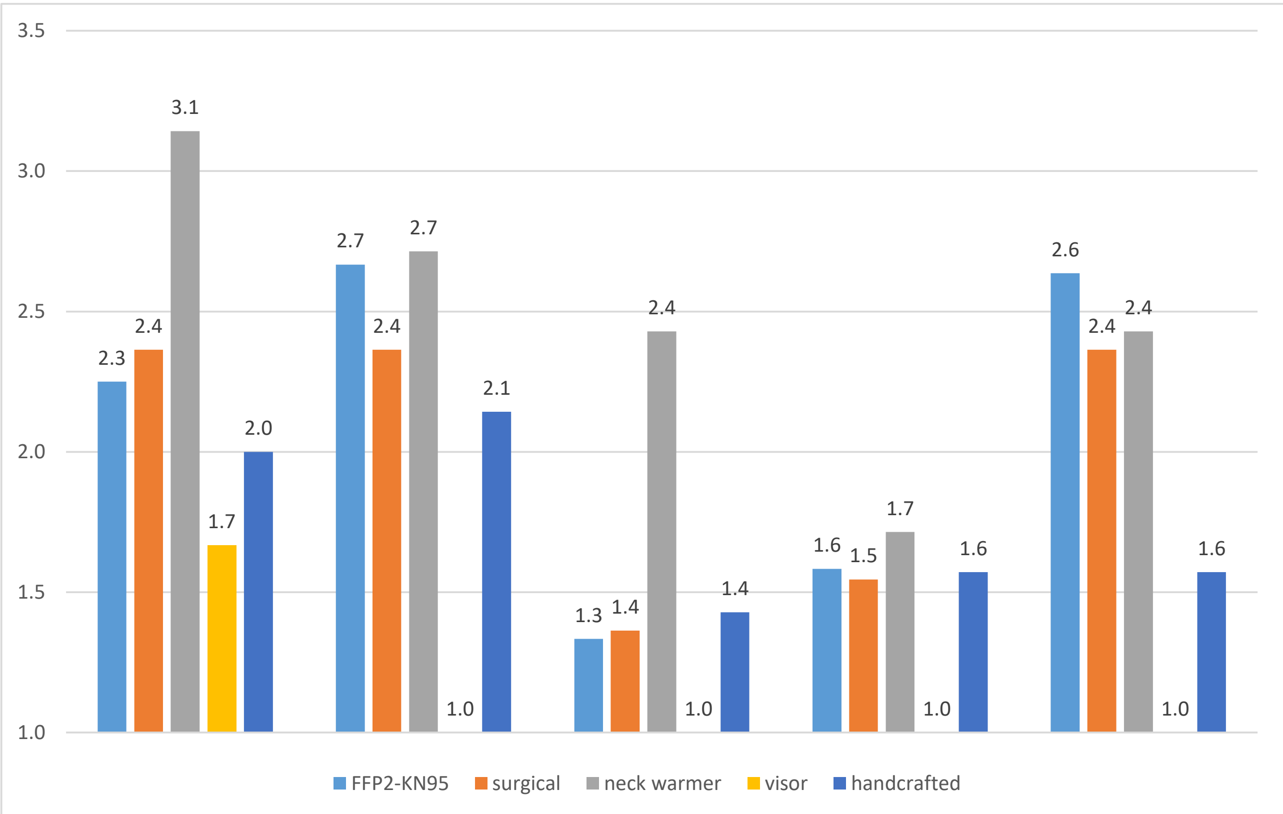

Figure 24. Results of the subjective analysis (per device type)

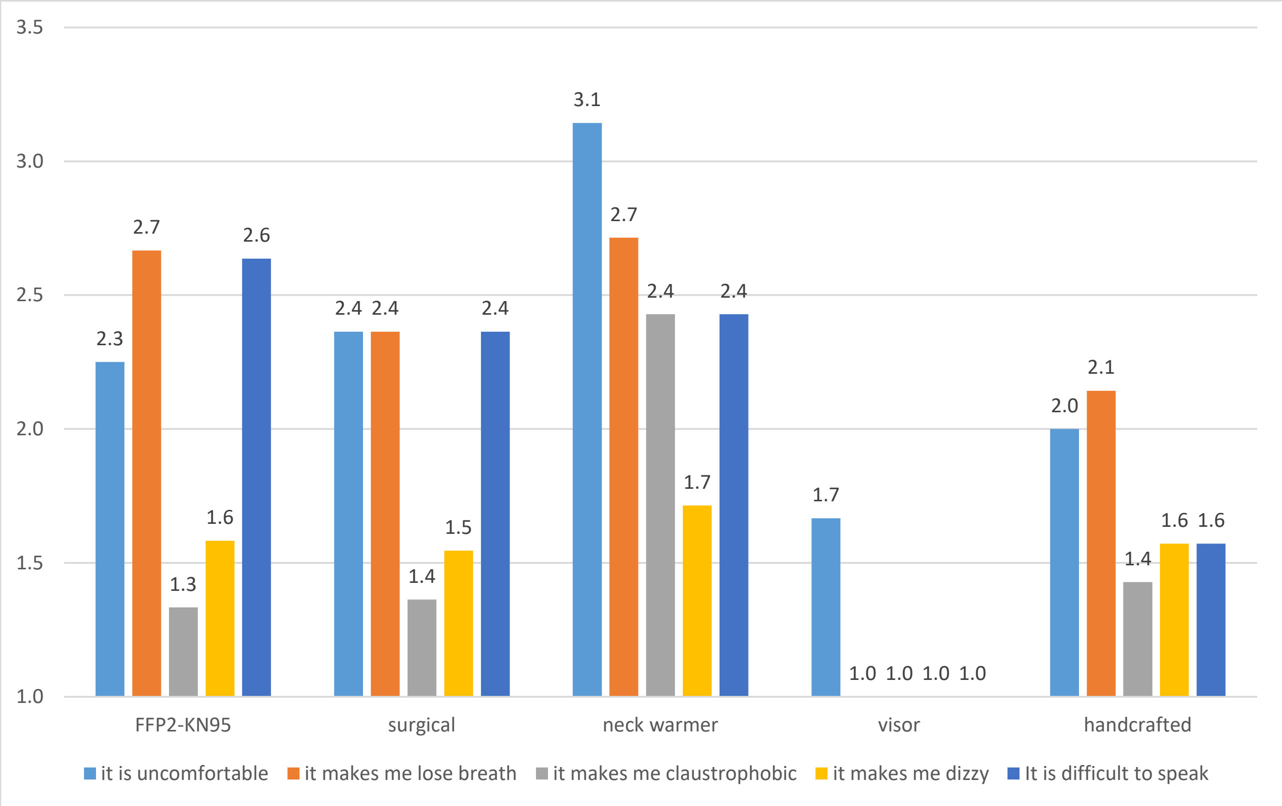

Figure 25. Results of the subjective analysis (per question)

In order to determine an indicator that summarizes the perception that the interviewees had, the average of the values of the five questions was calculated.

	Questionnaires results (mean value)
FFP2-KN95	2,1
Surgical mask	2,0
neck warmer	2,5
visor	1,1
Handcrafted mask	1,7

The subjective analysis underlined that:

- The visor has the lowest score, i.e. greater comfort and less dissatisfaction. Participants unanimously declared that this device does not modify speech and it has no influence on the breathing pattern.
- The device with the highest rating, that is the one that creates the most discomfort is the neck warmer.
- There is no difference between FFP2-KN95 and surgical masks, while on average the perception of respondents is better for handcrafted mask.

6.7 Data summary

Integrating measured data (CO_2 concentration, surface temperature variation) and those obtained from the questionnaires, the graph in Figure 26 is obtained.

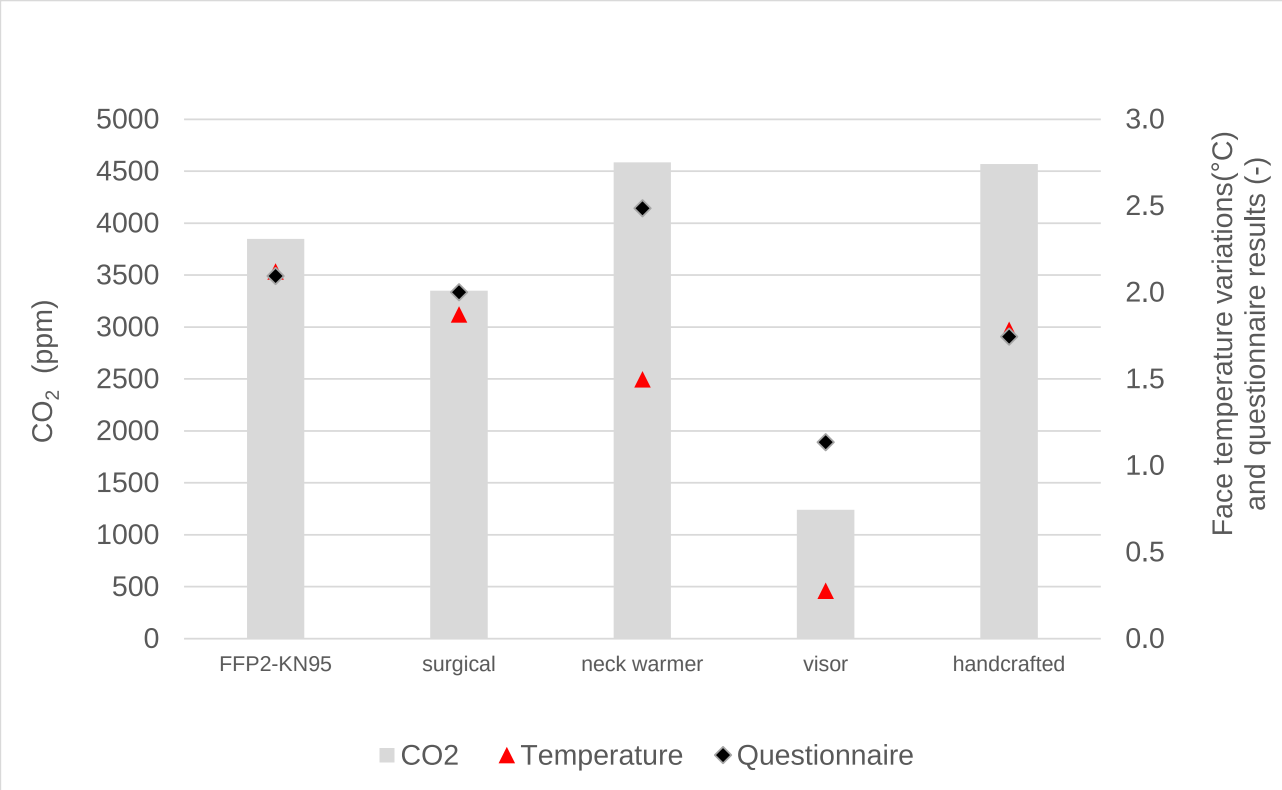

Figure 26. Summary of the measured and subjective data: inhaled (seated) CO_2 concentration, changes in face temperature and averages of the questionnaires

By superimposing the CO_2 concentration data with thermographic and subjective analyzes, it can be undelined that:

- CO_2 concentrations, average temperatures and satisfaction have similar trends;
- The visor is the device with an average inhaled CO_2 concentration lower than the other devices;
- There is no clear difference between FFP2-KN95 and surgical masks, both in terms of CO_2 concentration, surface temperature and satisfaction.

6.7 Device analysis

Tests were carried out by inserting the device, before use, inside a glass cylinder with the two ends open: on one end an activated carbon filter was placed, on the other the air filtered by the activated carbon, exposed to the device and sent to the analytical system.

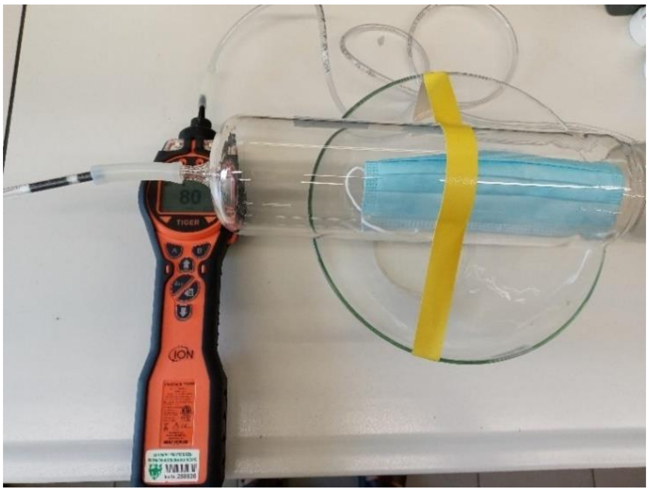

Figure 27. Device analysis

In these conditions the concentrations of formaldehyde and volatile organic compounds released by the devices were determined. For all devices, except one, the substances detected were very low in concentrations. For the surgical mask, shown above in Figure 27 (without CE certification), concentrations of hydrocarbons of about 2300 µg/m³ were detected as soon as it was removed from the plastic wrapping that contained it. After a few hours of exposure of the mask to the air, the concentrations dropped to an acceptable levels. Once washed, hand-made neck warmers and masks do not emit significant concentrations of polluting compounds.

Table 7. Device emissions analysis

Device	type	When opening the package TVOC ppb	4 hours after opening the package TVOC ppb	When opening the package Formaldehyd ppb
A	KN95	< 10	-	<5
B	Surgical mask - certified [a]	< 10	-	<5
C	Surgical mask without certification	2300	< 10	5
D	Surgical mask - certified [a]	< 10	-	<5

[a] *device certified according to EN 14683:2019*

Table 8. TVOC composition of Device C right after opening the package

Parameter	Results [µg/m^3]
Linear and branched HC	1343
2,4-dimethyl heptane	271
n-decan	187
N, N-Dimethyl acetamide	133
4 methyl octane	116
Toluene	56
4 methyl undecane	36
2,3,5 trimethyl hexane	34
n-dodecane	28
4 methyl heptane	25
2,3 dimethyl heptane	21
4.6 dimethyl dodecane	18
Ethanol	17
Sum without HC	940
Sum	2283

7. CONCLUSIONS

- The inhaled CO_2 concentration was quantified (as a unique indicator of air quality) for different types of nose and mouth covering devices.
- The percentage of re-inhaled CO_2 with respect to that of the breath was quantified for different types of nose and mouth covering devices.
- For the analyzed devices, the inhaled CO_2 concentrations are significantly lower than the exhaled ones.
- Even without the use of any devices, some of the exhaled air is re-inhaled. This effect is greater in still air conditions and less with moving air.
- The movement of air reduces the re-inhaled CO_2, even with the devices on.
- Inspired concentrations are higher than the guide values for indoor environments.
- The inspired concentrations are not significantly different from those detected in the environments in which we spend the major part of our time (schools, car, office, home).
- The tests did not show significant differences between the concentrations measured while sitting and under light effort (stepping up/down).
- The increase in surface temperature of the skin and the consequent greater sweating are the main cause of perceived discomfort.
- Devices do not absorb significant amounts of moisture.
- Some devices, as soon as the package is opened, release significant quantities of volatile organic compounds. Once exposed to the air for a few hours, the situation improves significantly.
- The environment in which a covering device is worn must have optimal ventilation characteristics, i.e. the CO_2 concentration must be less than 1000 ppm. Otherwise the inhaled CO_2 concentration while wearing the devices can increase significantly.

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