land

MDPI

Article

Virtual Forest Environment Influences Inhibitory Control

Viola Benedetti [1,†], Gioele Gavazzi [1,†], Fiorenza Giganti [1], Elio Carlo [2], Francesco Riccardo Becheri [3], Federica Zabini [4], Fabio Giovannelli [1,†] and Maria Pia Viggiano [1,*,†]

1 Department of Neuroscience, Psychology, Drug Research and Child's Health (NEUROFARBA), University of Florence, 50135 Florence, Italy; viola.benedetti@unifi.it (V.B.); gioele.gavazzi@unifi.it (G.G.); fiorenza.giganti@unifi.it (F.G.); fabio.giovannelli@unifi.it (F.G.)
2 Scuola di Psicoterapia Cognitiva, 00185 Rome, Italy; eliokarl@libero.it
3 Pian dei Termini Forest Therapy Station, 2311 Via Pratorsi, 51028 San Marcello Piteglio, Italy; ricerca@terapiaforestale.it
4 Institute for Bioeconomy, National Research Council, 10 Via Madonna del Piano, 50019 Sesto Fiorentino, Italy; federica.zabini@cnr.it
* Correspondence: mariapia.viggiano@unifi.it
† These authors contributed equally to this work.

Abstract: Exposure to natural green environments, whether through visual media or in person, can bring numerous benefits to physical and mental health. Given the restorative effects that natural forest environments have on the human mind, it is plausible to assume that these effects can also extend to cognitive processes, such as cognitive control, which are fundamental to higher-level cognitive function. In this study, we investigated whether viewing videos of urban or forest environments would have an impact on inhibitory control and attention in people with or without a past COVID-19 infection. To investigate the impact of virtual natural and urban videos on cognitive performance, 45 participants were recruited, and the exposure to forest vs. urban videos was assessed on a Go/No-Go task and an Attentional Network Test. The data showed that in both groups, exposure to the forest videos improved the inhibitory component. The results are discussed in the context of the well-established evidence of the beneficial effects of green environments.

Keywords: forest therapy; inhibitory control; Go/No-Go; virtual environment; COVID-19

Citation: Benedetti, V.; Gavazzi, G.; Giganti, F.; Carlo, E.; Becheri, F.R.; Zabini, F.; Giovannelli, F.; Viggiano, M.P. Virtual Forest Environment Influences Inhibitory Control. *Land* **2023**, *12*, 1390. https://doi.org/10.3390/land12071390

Academic Editors: Francesca Ugolini and David Pearlmutter

Received: 30 May 2023
Revised: 6 July 2023
Accepted: 10 July 2023
Published: 12 July 2023

1. Introduction

A growing number of studies have highlighted the significant impact of a natural environment, particularly forestry, on people's psychophysical well-being. As a matter of fact, forest exposure is associated with beneficial effects at both the physiological [1–4] and psychological levels [5–8].

In particular, the effects of being immersed in a natural environment on stress mitigation, anxiety, depression, mood, exhaustion disorder and quality of life [9–14] are now well assessed.

The effectiveness of forest therapy is now a consolidated fact; studies are increasingly oriented towards clarifying, for example, the extent to which natural elements are associated with reducing stress and improving immune function [15].

The positivity of natural exposure is so effective that it seems to be extended even to more challenging environments, such as urban green spaces, reporting beneficial effects on users' physical and mental health [16]. Therefore, greenery exposure seems to be highly effective, even if embedded in demanding settings and presented on a small scale.

Because of the apparent translatability of the natural positive effect, another aspect of growing interest is the type of greenery exposure, focusing on real vs. virtual. Virtual reality experiments are designed on the assumption that if there are health effects from natural exposition, then the same health benefits could be obtained from simulated forest immersion. This would be a way to provide therapy to patients who cannot use green spaces due to impaired walking or frailty caused by chronic disease. A growing interest, therefore, is focusing on the design of study protocols for simulated forest immersions [17]. Thus, alongside the significant results obtained in real forest contexts, the beneficial action on mind-body balance has also been obtained through virtual exposure to natural green environments [18–21]. Results were achieved with different degrees of immersivity, from VR protocols [22–24] to purely media (video or images) contents [25,26]. For example, in a previous study, virtual exposure to forest environments was shown to be effective in reducing perceived anxiety levels compared to urban videos [27].

In the face of an ever-increasing number of studies that have focused on the effects of greenery on the psychological/emotional dimension, only scarce literature has been dedicated to cognitive factors. Those few studies concern, especially, attention and memory. For example, Shin et al. [28] explored how interaction with forest and urban areas can affect performance in attention tasks among university students. The authors documented a significant improvement in performance when participants walked through the forest but not when they walked in urban areas. It should be noted there are no studies that have explored a possible effect of virtual forest immersion on cognitive control. Thus, although it is known that the emotional dimension (anxiety, depression, etc.) benefits from exposure to the real and virtual forest, we still do not know the impact that a simulated immersion could have on the cognitive component that sustains our oriented behavior.

On the basis of what is present in the literature, we have reason to believe that if contact with the forest has a beneficial and restorative action on the human mind, the impact could also be observed for cognitive control, a higher-order process involving subprocesses such as attention, memory and executive functions. This process coordinates thought and action in a flexible and adaptive way, allowing individuals to face the demands of the external environment in accordance with their personal goals [29]. Among the various processes involved in the subject's adaptation to the environment, the inhibition process plays a crucial role in suppressing inappropriate responses to the context. An impairment or lack of inhibition is likely to underlie disorders such as impulsivity, addiction and neurological and psychiatric conditions [30–35].

Starting from these premises, the aim of this work was to investigate (i) whether exposure to forest environments through video presentation can have an impact on cognitive control, focusing particularly on the inhibitory components, and (ii) whether this effect might depend on having contracted COVID-19, in view of the fact that the virus has impacted the cognitive system. In particular, it has been reported an alteration of inhibitory control after this condition (e.g., [36,37]). Moreover, the possible beneficial effect of a virtual exposition to forest environments is particularly relevant, considering the highlighted feeling of deprivation from, and need for, natural spaces of various forms, such as urban green areas, due to quarantine and isolation [38].

To this end, subjects were exposed to two conditions by viewing videos of forest and urban environments. In order to investigate inhibitory control, participants performed a Go/No-Go (GNG) task. Furthermore, since inhibition is a complex cognitive process that includes an attentive component, a second experiment was conducted to better understand the weight of attention in inhibitory control as a function of virtual exposure (i.e., the video content). In this follow-up, participants were asked to perform an Attentional Network Test (ANT) in addition to a GNG task. We opted for the ANT test as it offers a comprehensive assessment of various types of attention in a single sitting (alerting, orienting and executive functioning—e.g., [39,40]). In both experiments, participants' COVID-19 history was investigated. The effect of exposure to natural environments on cognitive control as a function of COVID-19 has been assessed. The analysis on COVID-19 (virus history vs. virus-free participants) has been run on cumulated GNG data from the first and second experiments to enhance statistical power.

Obtaining beneficial effects on the cognitive sphere conveyed by virtual naturalistic landscapes, a simple and affordable remedy, would have even more significant implications if we consider that not everyone, and not always, has real green spaces available to visit.

2. Materials and Methods of Experiment 1

2.1. Participants

Thirty healthy volunteers (22 women; M = 23.60; SD = 2.79; range = [from 21–33 y.o.]) with no history of neurological and psychiatric diseases (e.g., impulsivity disorders or ADHD) or drug abuse, with normal hearing and normal or corrected-to-normal vision, were included in the experiment. Participants were recruited from the students' community at the University of Florence via advertisements. During the experiment, no participant dropped out. We screened the sample regarding previous contraction of the coronavirus disease (COVID-19). Out of 30 participants, 24 subjects contracted the disease at least once between 2021 and 2022. This study was performed according to the Declaration of Helsinki and was approved by the Ethical Committee of the University of Florence (No. 253, 2023). Prior to the experimental session, each subject was blind to the purpose of this study, which was carefully explained after the completion of the experiment.

2.2. Materials

2.2.1. Video

The videos used were the same as those of Zabini and colleagues [27]. In the Forest condition, the video (5.09 min) consisted of forest environments located in the Apennine Mountains (43°57′ N, 11°10′ E and 44°01′ N, 11°00′ E). Shoots included coniferous and beech trees and water streams without human presence; audio was recorded as well. In the Urban condition, the video consisted of urban environments. The video (5.10 min) consisted of an urban environment located in downtown Prato (Italy). Shots included building scenes (office, front door and window) without people.

2.2.2. GNG Task

Visual stimuli consisted of white arrows presented on a gray background at the center of a touch-screen monitor. The arrows could be oriented up or down with respect to the horizontal axis. If the arrow was pointing upwards ('Go-Stimulus'), participants were instructed to tap on the arrow as quickly and accurately as possible. On the contrary, subjects were instructed to withhold the response if the arrow was pointing downwards ('No-Go Stimulus'). Each 'Go-Stimulus' and 'No-Go-Stimulus' remained on the screen for 200 ms. Between an arrow and the following, a blank was presented for 1000 ms (Figure 1). Trials order was randomized. The task consisted of 100 trials overall (80% 'Go-Stimulus' trials, 20% 'No-Go Stimulus' trials). The paradigm was preceded by a short training phase of 8 trials, of which 6 were 'Go-Stimulus' trials, and 2 were 'No-Go Stimulus' trials. OpenSesame 3.2.6 Kafkaesque Koffka [41] was used for stimuli production and response recording.

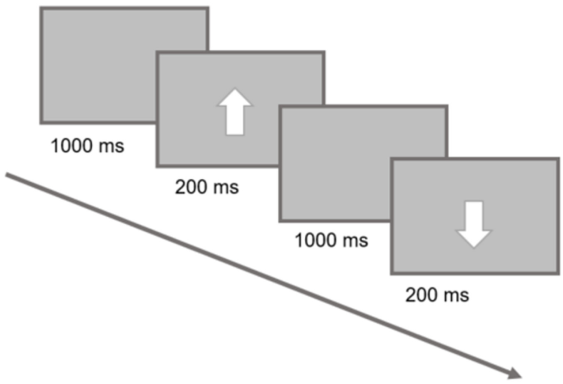

Figure 1. Trial structure of the GNG task. A blank was followed by a white arrow. Subjects were instructed to tap quickly and accurately for upwards arrows ('Go-Stimulus') and to withhold their response for downward arrows ('No-Go Stimulus'). Here a 'Go-Stimulus' trial, followed by a 'No-Go Stimulus' trial, is depicted.

2.3. Experimental Procedure

The procedure was carried out in two sessions, one week apart from each other. In each session, participants initially performed a GNG task. Subsequently, subjects were asked to watch and pay attention to either the forest or urban condition video. Finally, after the video, they were asked to perform a second run of the GNG (Figure 2). The order of video contents presentation of sessions was counterbalanced between participants. Subjects were positioned 57 cm away from the monitor.

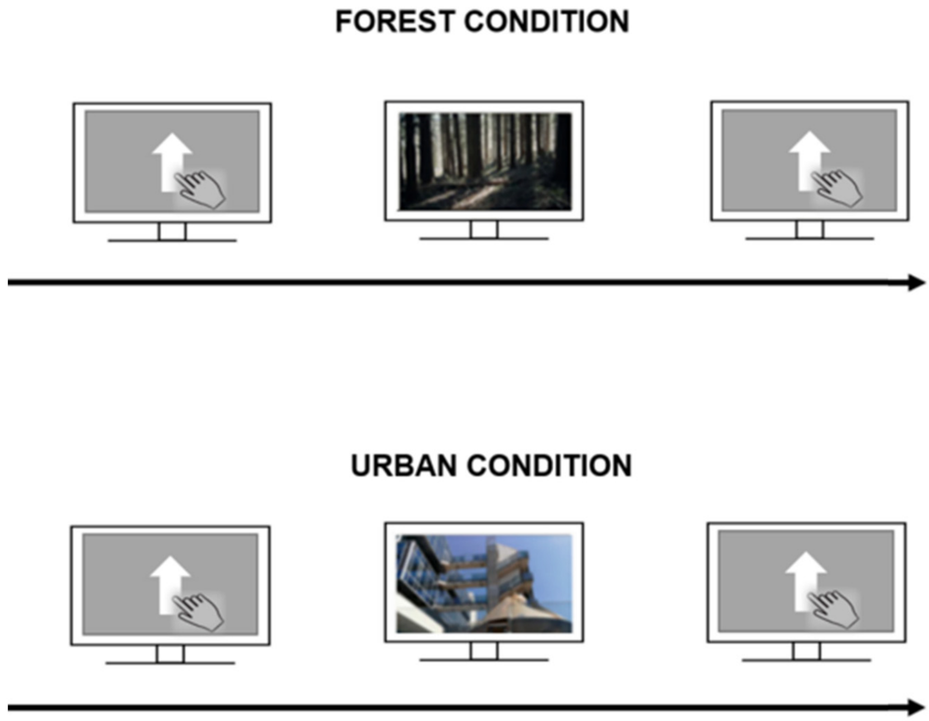

Figure 2. Experimental procedure. The upper part of the panel depicts the 'forest condition' while the lower part of the panel depicts the 'urban condition'. The experimental procedure was the same in both sessions, except for the video presented. The GNG was first performed (pre-video), the video was then administered, and another run of the task was run (post-video).

2.4. Analysis

2.4.1. GNG Task

For each subject, behavioral performance was first quantified by the following measures: mean reaction times (RTs), percentage of correct responses in the Go condition and the number of inhibitory failures in the No-Go condition. Measures were quantified for the prevideo and postvideo runs in both 'forest 'and 'urban' conditions. To assess the video effect on cognitive processing, we compared the Δ (post −pre video) of each measure between the 'forest' and 'urban' conditions by means of a percentile bootstrap inference. Bootstrapping is a nonparametric method based on a data-driven simulation that is often applied as a substitute to standard parametric approaches as it does not rely on parametric assumptions [42,43]. The Bonferroni-corrected alpha level was set to 0.017.

Statistical analysis (two-tailed) was run using MATLAB (version 2020b; The MathWorks Inc., Natik, Mass, Portola Valley, CA, United States).

3. Results of Experiment 1

GNG Task

Table 1 provides details on behavioral performance in the Go/No-Go task during both the 'forest' and 'urban' conditions.

Table 1. GNG measures (means and standard deviations).

Measures	Pre-Video	Post-Video	Δ
	Forest		
Go RT (ms)	427.0 ± 64	434.5 ± 95	7.5 ± 80
Go accuracy (%)	88.5 ± 11	90.2 ± 12	1.7 ± 6
No-Go commission (*n*)	6.6 ± 4	4.2 ± 3	−2.4 ± 3
	Urban		
Go RT (ms)	435.4 ± 73	420.0 ± 60	−15.4 ± 43
Go accuracy (%)	89.8 ± 11	89.8 ± 11	0.0 ± 5
No-Go commission (*n*)	5.2 ± 3	4.8 ± 4	−0.4 ± 2

The percentile bootstrap analysis revealed a significantly greater reduction in commission errors (*n*) after viewing the 'forest video' compared to the 'urban video', with an estimated difference (forest − urban) of −2.03 (CI = [−3.4, −0.7], p = 0.003)—Figure 3. There were no other significant differences between conditions, with a nonsignificant ($p > \alpha$) estimated difference of 22.7 (ms) for RTs and 1.7 (%) for Go accuracy.

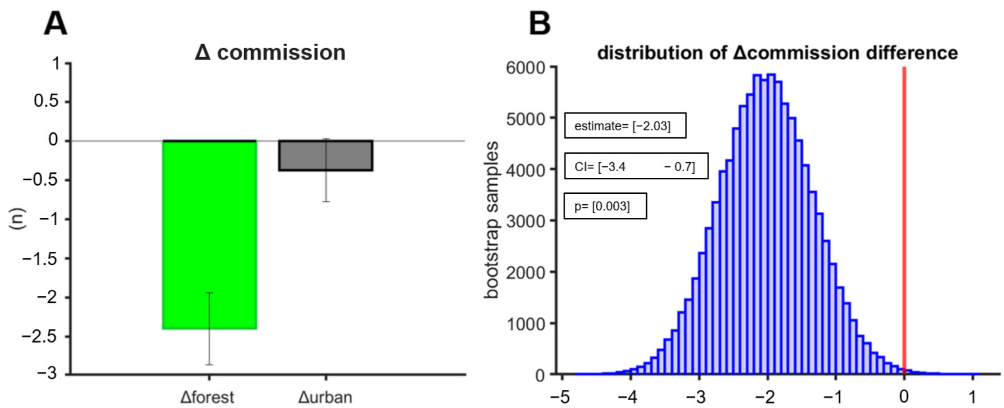

Figure 3. (**A**) Bar graph of mean Δ commission errors (±SE). The green bar represents the variation in performance after the exposition to the forest video, and the grey bar represents the variation in performance after the exposition to the urban video. (**B**) Histogram of bootstrapped means difference between conditions (Δforest − Δurban) per commission errors. The red line represents the null value (0, i.e., absence of difference) with respect to the bootstrapped distribution. Mean estimate, 95% C.I. and *p*-value are shown in the graph.

In sum, viewing videos of urban or forest environments had a different impact on inhibitory control. Our results highlight a significantly greater decrease in commission errors following the viewing of the 'forest' compared to the 'urban' video. Inhibitory control seems, therefore, enhanced by the exposition of natural rather than urban scenery. This result emerges clearly. However, to disengage the inhibitory component from the attentional one, a second experiment was performed. The need to further explore the data arises from the following reasoning. Studies have reported that natural exposure is associated with the restoration of attention, improving the ability to focus on a specific task [44]. Here we found an effect of natural presentation on inhibitory control, a complex executive function that includes attention. A second experiment, hence, elucidated the role of general attention restoration versus inhibition enhancement. In this second experiment, in addition to the investigation of inhibition via the GNG task, we explicitly assessed the effect of virtual natural scenery on different aspects of the attentional network and cognitive control system using the ANT. By employing this approach, it would be feasible to evaluate the extent to which the observed enhancement in inhibitory control might be influenced by the effects of attention.

As a limitation of this first experiment, it was not possible to analyze the performance of the subjects who had contracted COVID-19 and those who had not contracted it, given the small number of COVID-free subjects.

Therefore, the second experiment also aimed to increase the number of subjects who had not contracted COVID so that performance could be compared.

4. Materials and Methods of Experiment 2

4.1. Participants

Fifteen healthy volunteers (12 women; M = 23.40; SD = 2.61; range = [from 21–30 y.o.]) with no history of neurological and psychiatric diseases (e.g., impulsivity disorders or ADHD) or drug abuse, with normal hearing and normal or corrected-to-normal vision, were included in this study. Participants were recruited from the students' community at the University of Florence via advertisements. During the experiment, no participant dropped out. Out of 15 participants, 7 subjects contracted the disease at least once between 2021 and 2022. This study was performed according to the Declaration of Helsinki and was approved by the Ethical Committee of the University of Florence (No. 253, 2023). All participants gave their written informed consent to the procedure and the processing of personal data. Prior to the experimental session, each subject was blind to the purpose of this study, which was carefully explained after the completion of the experiment.

4.2. Materials

4.2.1. Video

The videos used were the same as Zabini and colleagues [27] used in the previous experiment. See Section 2.2.1 for description.

4.2.2. GNG Task

The GNG task corresponded exactly to the one used in the previous experiment; see Section 2.2.2 for description.

4.2.3. ANT

ANT test is the most comprehensive task to assess the different functions of attention. Namely, the alerting, orienting and executive functioning of attention—e.g., [39,40]. Visual stimuli consisted of 5 black arrows, organized in a horizontal row and presented above or below the screen center, which was pointed out by a fixation cross. The fixation cross stayed on screen throughout the entire task. Arrows could point either left or right. Participants were instructed to report the pointing direction of the central arrow out of the five as fast and accurately as possible by pressing the corresponding arrow key on the keyboard. The arrows on the side were distractors; they flanked the central one by either pointing in the same direction ('congruent condition') or the opposite direction ('incongruent condition'), see Figure 4C. The timing of the arrows' appearance was sometimes predicted by the appearance of one or two asterisks that functioned as a warning cue. Participants were informed that asterisks always preceded the arrows by 500 ms. Participants were also informed that if only one asterisk appeared, its position was also predictive of the location of the incoming arrows, creating a spatial expectation in participants. Asterisks could appear either above, below or in place of the fixation cross. There were four possible warning cue types: 'no-cue type' (no asterisks), 'center-cue type' (asterisk on top of fixation cross), 'spatial-cue type' (one asterisk either above or below the fixation cross) and 'double-cue type' (two asterisks above and below the fixation cross). Cue types are depicted in Figure 4B. The trial structure consisted of an initial fixation cross presented for a random interval between 400 and 1000 ms. The initial fixation was followed by the presentation of one of the four warning cue possibilities for 100 ms. A second fixation followed for 400 ms before the arrow targets were presented. Arrows stayed on screen for 1500 ms or until key-press. A final inter-trial fixation appeared for a conditional duration based on a defined trial time of 3500 ms (Figure 4A). Trials were 128 overall, 64 were congruent and 64 incongruent, with 32 trials per each warning cue type. The task was divided into 4 blocks of 32 trials each. There was an initial practice phase of 32 trials. The task used originated from the Centre for Research on Safe Driving (CRSD) by Docksteader and Scott (http://docksteaderluke.com, http://krssctt.com, accessed on 20 December 2021).

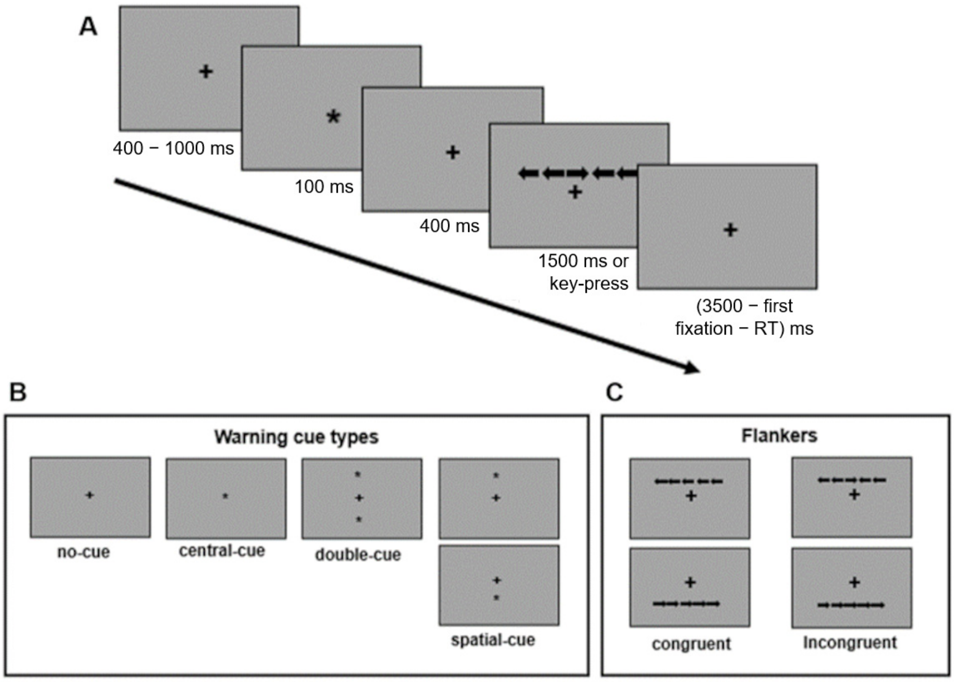

Figure 4. (**A**) Trial structure of the ANT. A fixation cross (+) was presented in the center of the screen and followed by a warning cue (*). After a second fixation, target arrows were then presented and followed by the inter-trial fixation cross. (**B**) Warning cue types (no-cue, central-cue, double-cue, spatial-cue type) are depicted, from the left to the right part of the panel, respectively. (**C**) Congruent and incongruent conditions example from left to right, respectively.

4.3. Experimental Procedure

The procedure corresponded to the one used in the previous experiment. Moreover, to control for attentional effects, the ANT test, after the video exposure and before the last GNG task, was finally performed.

4.4. Analysis

4.4.1. GNG Task

The same analysis as in the previous experiment was run on the GNG data; see Section 2.4.1.

4.4.2. ANT

The alerting, orienting and conflict efficiency network scores were calculated. In particular, the scores were calculated as the following differences in RTs: alerting = RT no cue—RT double cue, Orienting = RT center cue—RT spatial cue, and Conflict Efficiency = RT incongruent—RT congruent. Each network score was calculated for both 'forest' and 'urban' conditions. Each score was compared between conditions by means of a percentile bootstrap inference [42,43]. The Bonferroni-corrected alpha level was set to 0.017.

4.4.3. COVID-19 Effects

To reach an adequate number of subjects for each group, the analysis was conducted by cumulating the COVID-19-affected and COVID-19-free subjects of the first and second experiments for the GNG task. Each GNG measure (RTs, accuracy and commissions) was compared between groups by means of a percentile bootstrap inference [42,43]. The same analysis was used to evaluate the video forest effectiveness within each group by comparing the Δ (post −−pre video) of each measure between the 'forest' and 'urban' conditions. The Bonferroni-corrected alpha level was set to 0.017.

Statistical analysis (one-tailed) was run using MATLAB (version 2020b; The MathWorks Inc.) and R (version 2021.9.1.372; R Core Team, 2021).

5. Results of Experiment 2

5.1. GNG Task

Table 2 provides details on behavioral performance in the GNG task during both the 'forest' and 'urban' conditions.

Table 2. GNG measures (means and standard deviations).

Measures	Pre-Video	Post-Video	Δ
	Forest		
Go RT (ms)	389.2 ± 53	400.1 ± 58	10.9 ± 42
Go accuracy (%)	94.1 ± 4	95.2 ± 5	1.1 ± 4
No-Go commission (*n*)	4.0 ± 3	2.9 ± 2	−1.1 ± 2
	Urban		
Go RT (ms)	418.5 ± 86	403.1 ± 68	−15.4 ± 52
Go accuracy (%)	95.1 ± 5	94.2 ± 6	−0.9 ± 3
No-Go commission (*n*)	2.9 ± 3	3.3 ± 3	0.5 ± 2

There was a significantly greater reduction in commission errors with an estimated Δ (forest − urban) of −1.53 (*n*) for the forest, compared to the urban, condition (CI = [−2.9, −0.3], $p = 0.005$). All other delta variables of interest did not show any significant differences ($p > \alpha$) between conditions, with an estimate of 26 (ms) for go RT and 2.04 (%) for go accuracy. We controlled by means of a t-test (Bonferroni corrected) for potential differences in cumulated GNG data (go accuracy, go RTs and commissions) between men ($n = 11$) and women ($n = 34$) and we did not find any significant differences.

5.2. ANT

No significant differences ($p > \alpha$) were found for any of the network scores, with an estimate of 3.13 (ms) for the alert score, an estimate of −6.47 (ms) for the conflict score and an estimate of 1.64 (ms) for the orient score.

5.3. COVID-19 Effects

The analysis revealed a significant difference between groups for Go accuracy (see Table 3), with COVID-19-free subjects showing overall higher Go accuracy than COVID-19-affected subjects, with an estimate (COVID-19 free–affected) of 3.63% (CI = [1.3, 6.30], $p = 0.001$). Moreover, a trend emerged for commission errors, with COVID-19-free subjects reporting less commission than affected participants, with an estimate of −0.84 (CI = [−1.8, 0.2], $p = 0.058$). There was no significant effect ($p > \alpha$) for RTs.

Table 3. GNG measures (mean and standard deviations) for COVID-19 free and COVID-19 affected groups.

Measures	COVID-19 Free	COVID-19 Affected
Go RT (ms)	429.8 ± 91	416.2 ± 62
Go accuracy (%)	93.8 ± 5	90.1 ± 11
No-Go commission (*n*)	4.0 ± 3	4.8 ± 4

In addition, a significantly greater reduction in commission for the 'forest video' compared to the 'urban video' has been found within both groups (Figure 5). In particular, COVID-19-free participants reported a significant difference, with an estimate (forest − urban) of −1.71 (CI = [−3.3, −0.1], p = 0.015). COVID-19-affected participants reported a significant difference, with an estimate of −1.94 (CI = [−3.2, −0.7], p = 0.001). All the other measures did not show any significant differences.

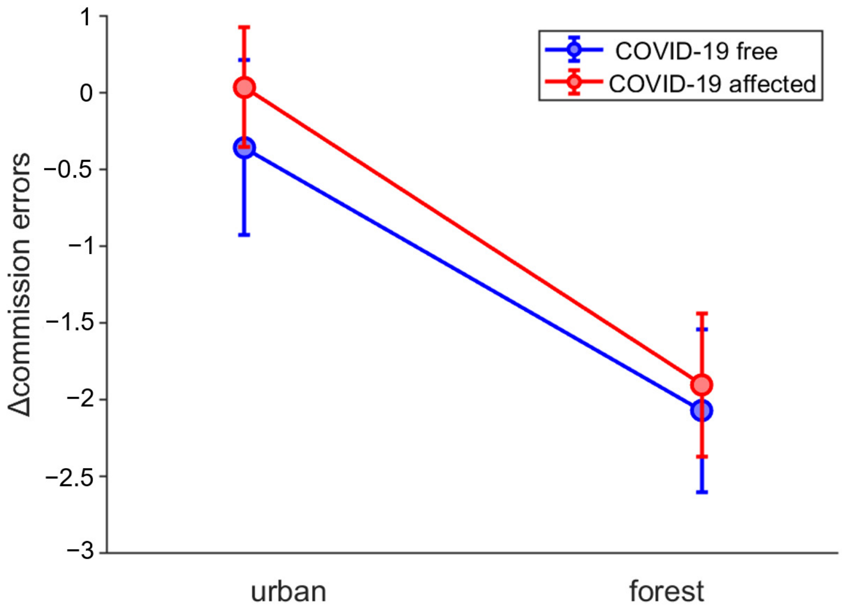

Figure 5. Plot for mean Δcommission errors (±SE) between urban (left side) vs. forest (right side) conditions in COVID-19-free participants (blue line) and COVID-19-affected participants (red line).

In sum, there was a significantly greater decrease in commission errors after the 'forest video' compared to the 'urban video', confirming findings from experiment 1. Virtual natural environment exposure does modulate inhibitory performance in a beneficial manner. Moreover, no effect of video content was observed in the ANT for the three network measures.

Data here suggest that the virtual forest exposure effect on performance emerges differently depending on attentive and cognitive control demand requirements, with a greater result showing when inhibition is involved. This finding is addressed in the Section 6.

A comforting finding is that participants with COVID-19 benefited from forest exposure similarly to subjects COVID-19 free. In addition, in line with other studies [45–47], results seem to show cognitive control consequences due to the virus in selection and suppression processes involved in response inhibition [48].

6. General Discussion

The effect of exposure to virtual natural vs. urban environments on cognitive control and attention was investigated in people with and without a past COVID-19 infection. Results of the GNG task indicate enhanced inhibitory performance following the 'forest' compared to the 'urban' video. On the other hand, the absence of significant effects associated with the ANT task suggests the lack of a behavioral modulation of the virtual natural scenery on different attentional components.

Cognitive control is widely recognized to rely on two key components: an excitatory element and an inhibitory element. Metanalyses of neural correlates and single studies provide evidence of the vital role played by the attentional system in the excitatory component, indicating the core hub in the alertness network, whereas the inhibitory component is regulated by the inhibitory network [48–53]. In our study, we did not find any significant effect of video exposure on the attentional task. This lack of modulation on attentional aspects suggests that the effect of exposure is more consistent with purely inhibitory aspects.

We, therefore, hypothesize that the effect in the GNG task could be primarily attributable to a modulation of the inhibitory network rather than the attentional component of inhibition.

The observed reduction in commission errors seems not entirely amenable to attention, that is, for instance, by improving the alerting system that may facilitate inhibitory control. Thus, the inhibitory network per se might be the trigger responsible for the observed results.

Previous studies, however, have highlighted improved attention when subjects were exposed to real forest environments [7,54–58]. Thus, if the impact of virtual forest exposure had the same as that of real exposure on the two cognitive processes investigated here, we would expect to see a noticeable improvement also in the attention process. However, our observations in this study indicate that the improvement in the attention networks was not significant, at least at the inhibitory level. This indicates that attentive and cognitive control task loads modulate in a different manner the degree of performance variation depending on the type of exposure (virtual vs. real). Indeed, it is well known in the literature that exposure to relaxing videos improves prosocial behavior and reduces crime rates (e.g., [59,60]). Hence, the main limitation of the current study is the absence of a relaxing control video to ascertain the origin of the outcomes derived from video exposure. Further studies will be necessary to determine how crucial the contribution of the presented video's content is.

In further analyses, we examined whether exposure to virtual forest environments could have impacted differently inhibitory control in participants who contracted COVID-19 with respect to those who had not. It is known that COVID-19 infection can cause cognitive deficits (e.g., [61,62]), with consequences on frontal lobe functioning, specifically inhibitory control (e.g., [36,37]). These consequences encompass the executive domain, with affected individuals showing lower cognitive control compared to healthy controls up to several months after the infection [45]. Our results seem to corroborate the literature, as a worse performance in the GNG task emerged for COVID-19 participants with respect to participants who reported never having contracted the virus.

As further results, with a comforting connotation, we observed that subjects COVID-19 benefited from forest exposure as well as subjects who have not contracted the virus.

Thus, assessing whether natural exposition represents an effective tool to enhance cognitive control in individuals with a COVID-19 history is, therefore, relevant. However, further investigations could facilitate a deeper comprehension of the prospective inhibitory control deficits provoked by COVID-19 infections and offer potential mitigation techniques to alleviate the detrimental impacts encountered by convalescent patients. As shown herein, one such intervention that warrants exploration is forest therapy, either in a virtual or physical context, which has demonstrated multiple physical and psychological health benefits and may have relevance for addressing the inhibitory control impairments that COVID-19 survivors may encounter.

Findings from this study reveal, therefore, applicative implications. The beneficial effect of natural exposure could prove useful to the many conditions where inhibition is impaired. Given the virtual modality of our exposure, these results seem particularly useful in hospitalization contexts or whenever mobility is not an option. Implications might extend to realities where inhibitory control is vital, such as air traffic controllers or pilots where split-second decisions are needed. The positive influence of natural exposure should be taken into consideration while designing ergonomic contexts to maximize inhibitory performance.

Author Contributions: Conceptualization, M.P.V., G.G., F.G. (Fiorenza Giganti) and F.G. (Fabio Giovannelli); methodology, G.G., V.B. and F.G. (Fabio Giovannelli); formal analysis, V.B.; writing—original draft preparation, M.P.V., F.G. (Fiorenza Giganti) and G.G.; writing—review and editing, F.Z., E.C., F.R.B. and F.G. (Fabio Giovannelli). All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Janik, H.; Kraft, K.; Trabandt, A. Efficacy of Healing Forest Therapy for Patients with Chronic Obstructive Pulmonary Disease (COPD). *Eur. J. Integr. Med.* **2021**, *48*, 101944. [CrossRef]
2. Wu, Q.; Ye, B.; Lv, X.; Mao, G.; Wang, S.; Chen, Z.; Wang, G. Adjunctive Therapeutic Effects of Cinnamomum Camphora Forest Environment on Elderly Patients with Hypertension. *Int. J. Gerontol.* **2020**, *14*, 327–331. [CrossRef]
3. Bikomeye, J.C.; Balza, J.S.; Kwarteng, J.L.; Beyer, A.M.; Beyer, K.M.M. The Impact of Greenspace or Nature-Based Interventions on Cardiovascular Health or Cancer-Related Outcomes: A Systematic Review of Experimental Studies. *PLoS ONE* **2022**, *17*, e0276517. [CrossRef]
4. Chae, Y.; Lee, S.; Jo, Y.; Kang, S.; Park, S.; Kang, H. The Effects of Forest Therapy on Immune Function. *Int. J. Environ. Res. Public. Health* **2021**, *18*, 8440. [CrossRef]
5. Corazon, S.S.; Sidenius, U.; Poulsen, D.V.; Gramkow, M.C.; Stigsdotter, U.K. Psycho-Physiological Stress Recovery in Outdoor Nature-Based Interventions: A Systematic Review of the Past Eight Years of Research. *Int. J. Environ. Res. Public. Health* **2019**, *16*, 1711. [CrossRef]
6. Kotera, Y.; Richardson, M.; Sheffield, D. Effects of Shinrin-Yoku (Forest Bathing) and Nature Therapy on Mental Health: A Systematic Review and Meta-Analysis. *Int. J. Ment. Health Addict.* **2022**, *20*, 337–361. [CrossRef]
7. Antonelli, M.; Donelli, D.; Carlone, L.; Maggini, V.; Firenzuoli, F.; Bedeschi, E. Effects of Forest Bathing (Shinrin-Yoku) on Individual Well-Being: An Umbrella Review. *Int. J. Environ. Health Res.* **2022**, *32*, 1842–1867. [CrossRef]
8. Donelli, D.; Meneguzzo, F.; Antonelli, M.; Ardissino, D.; Niccoli, G.; Gronchi, G.; Baraldi, R.; Neri, L.; Zabini, F. Effects of Plant-Emitted Monoterpenes on Anxiety Symptoms: A Propensity-Matched Observational Cohort Study. *Int. J. Environ. Res. Public. Health* **2023**, *20*, 2773. [CrossRef]
9. Bang, K.S.; Lee, I.S.; Kim, S.J.; Song, M.K.; Park, S.E. The Effects of Urban Forest-walking Program on Health Promotion Behavior, Physical Health, Depression, and Quality of Life: A Randomized Controlled Trial of Office-workers. *J. Korean Acad. Nurs.* **2016**, *46*, 140–148. [CrossRef]
10. Chun, M.H.; Chang, M.C.; Lee, S.-J. The Effects of Forest Therapy on Depression and Anxiety in Patients with Chronic Stroke. *Int. J. Neurosci.* **2017**, *127*, 199–203. [CrossRef]
11. Brown, D.K.; Barton, J.L.; Pretty, J.; Gladwell, V.F. Walks4Work: Assessing the Role of the Natural Environment in a Workplace Physical Activity Intervention. *Scand. J. Work. Environ. Health* **2014**, *40*, 390–399. [CrossRef] [PubMed]
12. Huber, D.; Grafetstätter, C.; Proßegger, J.; Pichler, C.; Wöll, E.; Fischer, M.; Dürl, M.; Geiersperger, K.; Höcketstaller, M.; Frischhut, S.; et al. Green Exercise and Mg-ca-SO4 Thermal Balneotherapy for the Treatment of Non-Specific Chronic Low Back Pain: A Randomized Controlled Clinical Trial. *BMC Musculoskelet. Disord.* **2019**, *20*, 221. [CrossRef] [PubMed]
13. Meneguzzo, F.; Albanese, L.; Antonelli, M.; Baraldi, R.; Becheri, F.R.; Centritto, F.; Donelli, D.; Finelli, F.; Firenzuoli, F.; Margheritini, G.; et al. Short-Term Effects of Forest Therapy on Mood States: A Pilot Study. *Int. J. Environ. Res. Public. Health* **2021**, *18*, 9509. [CrossRef]
14. Sonntag-Öström, E.; Nordin, M.; Lundell, Y.; Dolling, A.; Wiklund, U.; Karlsson, M.; Carlberg, B.; Slunga Järvholm, L. Restorative Effects of Visits to Urban and Forest Environments in Patients with Exhaustion Disorder. *Urban For. Urban Green.* **2014**, *13*, 344–354. [CrossRef]
15. Frumkin, H.; Bratman, G.N.; Breslow, S.J.; Cochran, B.; Kahn, J.P.H.; Lawler, J.J.; Levin, P.S.; Tandon, P.S.; Varanasi, U.; Wolf, K.L.; et al. Nature Contact and Human Health: A Research Agenda. *Environ. Health Perspect.* **2017**, *125*, 075001. [CrossRef] [PubMed]
16. Ugolini, F.; Massetti, L.; Calaza-Martínez, P.; Cariñanos, P.; Dobbs, C.; Ostoić, S.K.; Marin, A.M.; Pearlmutter, D.; Saaroni, H.; Šaulienė, I.; et al. Effects of the COVID-19 Pandemic on the Use and Perceptions of Urban Green Space: An International Exploratory Study. *Urban For. Urban Green.* **2020**, *56*, 126888. [CrossRef]
17. Ross, A.M.; Jones, R.J.F. Simulated Forest Immersion Therapy: Methods Development. *Int. J. Environ. Res. Public. Health* **2022**, *19*, 5373. [CrossRef]
18. Jo, H.; Song, C.; Miyazaki, Y. Physiological Benefits of Viewing Nature: A Systematic Review of Indoor Experiments. *Int. J. Environ. Res. Public. Health* **2019**, *16*, 4739. [CrossRef]
19. White, M.P.; Yeo, N.L.; Vassiljev, P.; Lundstedt, R.; Wallergård, M.; Albin, M.; Lõhmus, M. A Prescription for "Nature"-the Potential of Using Virtual Nature in Therapeutics. *Neuropsychiatr. Dis. Treat.* **2018**, *14*, 3001–3013. [CrossRef]
20. Wang, X.; Shi, Y.; Zhang, B.; Chiang, Y. The Influence of Forest Resting Environments on Stress Using Virtual Reality. *Int. J. Environ. Res. Public. Health* **2019**, *16*, 3263. [CrossRef]
21. Grassini, S.; Segurini, G.V.; Koivisto, M. Watching Nature Videos Promotes Physiological Restoration: Evidence From the Modulation of Alpha Waves in Electroencephalography. *Front. Psychol.* **2022**, *13*, 871143. [CrossRef]
22. Valtchanov, D.; Barton, K.R.; Ellard, C. Restorative Effects of Virtual Nature Settings. *Cyberpsychology Behav. Soc. Netw.* **2010**, *13*, 503–512. [CrossRef]
23. Litleskare, S.; MacIntyre, E.T.; Calogiuri, G. Enable, Reconnect and Augment: A New ERA of Virtual Nature Research and Application. *Int. J. Environ. Res. Public. Health* **2020**, *17*, 1738. [CrossRef] [PubMed]
24. Yu, C.-P.; Lee, H.-Y.; Luo, X.-Y. The Effect of Virtual Reality Forest and Urban Environments on Physiological and Psychological Responses. *Urban For. Urban Green.* **2018**, *35*, 106–114. [CrossRef]
25. Mostajeran, F.; Krzikawski, J.; Steinicke, F.; Kühn, S. Effects of Exposure to Immersive Videos and Photo Slideshows of Forest and Urban Environments. *Sci. Rep.* **2021**, *11*, 3994. [CrossRef] [PubMed]

26. Van den Berg, A.E.; Joye, Y.; Koole, S.L. Why Viewing Nature Is More Fascinating and Restorative than Viewing Buildings: A Closer Look at Perceived Complexity. *Urban For. Urban Green.* **2016**, *20*, 397–401. [CrossRef]
27. Zabini, F.; Albanese, L.; Becheri, F.R.; Gavazzi, G.; Giganti, F.; Giovanelli, F.; Gronchi, G.; Guazzini, A.; Laurino, M.; Li, Q.; et al. Comparative Study of the Restorative Effects of Forest and Urban Videos during COVID-19 Lockdown: Intrinsic and Benchmark Values. *Int. J. Environ. Res. Public. Health* **2020**, *17*, 8011. [CrossRef]
28. Shin, W.S.; Shin, C.S.; Yeoun, P.S.; Kim, J.J. The Influence of Interaction with Forest on Cognitive Function. *Scand. J. For. Res.* **2011**, *26*, 595–598. [CrossRef]
29. Michael, S.G.; Richard, B.I.; George, R.M. *Richard Cognitive Neuroscience: The Biology of the Mind: Fourth International Student Edition*; W.W.Norton: New York, NY, USA, 2013; ISBN 978-0-393-92228-8.
30. Barkley, R.A. Behavioral Inhibition, Sustained Attention, and Executive Functions: Constructing a Unifying Theory of ADHD. *Psychol. Bull.* **1997**, *121*, 65–94. [CrossRef]
31. Aron, A.R.; Fletcher, P.C.; Bullmore, E.T.; Sahakian, B.J.; Robbins, T.W. Stop-Signal Inhibition Disrupted by Damage to Right Inferior Frontal Gyrus in Humans. *Nat. Neurosci.* **2003**, *6*, 115–116. [CrossRef]
32. Gavazzi, G.; Lenge, M.; Bartolini, E.; Bianchi, A.; Agovi, H.; Mugnai, F.; Guerrini, R.; Giordano, F.; Viggiano, M.P.; Mascalchi, M. Left Inferior Frontal Cortex Can Compensate the Inhibitory Functions of Right Inferior Frontal Cortex and Pre-Supplementary Motor Area. *J. Neuropsychol.* **2019**, *13*, 503–508. [CrossRef]
33. Gavazzi, G.; Rossi, A.; Orsolini, S.; Diciotti, S.; Giovannelli, F.; Salvadori, E.; Pantoni, L.; Mascalchi, M.; Viggiano, M.P. Impulsivity Trait and Proactive Cognitive Control: An FMRI Study. *Eur. J. Neurosci.* **2019**, *49*, 1171–1179. [CrossRef] [PubMed]
34. Gavazzi, G.; Orsolini, S.; Salvadori, E.; Bianchi, A.; Rossi, A.; Donnini, I.; Rinnoci, V.; Pescini, F.; Diciotti, S.; Viggiano, M.P.; et al. Functional Magnetic Resonance Imaging of Inhibitory Control Reveals Decreased Blood Oxygen Level Dependent Effect in Cerebral Autosomal Dominant Arteriopathy with Subcortical Infarcts and Leukoencephalopathy. *Stroke* **2019**, *50*, 69–75. [CrossRef] [PubMed]
35. Feil, J.; Sheppard, D.; Fitzgerald, P.B.; Yücel, M.; Lubman, D.I.; Bradshaw, J.L. Addiction, Compulsive Drug Seeking, and the Role of Frontostriatal Mechanisms in Regulating Inhibitory Control. *Neurosci. Biobehav. Rev.* **2010**, *35*, 248–275. [CrossRef]
36. Carbone, F.; Zamarian, L.; Rass, V.; Bair, S.; Ritter, M.; Beer, R.; Mahlknecht, P.; Heim, B.; Limmert, V.; Peball, M.; et al. Cognitive Dysfunction 1 Year after COVID-19: Evidence from Eye Tracking. *Ann. Clin. Transl. Neurol.* **2022**, *9*, 1826–1831. [CrossRef]
37. Chen, Y.; Yang, W.; Chen, F.; Cui, L. COVID-19 and Cognitive Impairment: Neuroinvasive and Blood–brain Barrier Dysfunction. *J. Neuroinflamm.* **2022**, *19*, 222. [CrossRef] [PubMed]
38. Ugolini, F.; Massetti, L.; Pearlmutter, D.; Sanesi, G. Usage of Urban Green Space and Related Feelings of Deprivation during the COVID-19 Lockdown: Lessons Learned from an Italian Case Study. *Land Use Policy* **2021**, *105*, 105437. [CrossRef]
39. Posner, M.I.; Petersen, S.E. The Attention System of the Human Brain. *Annu. Rev. Neurosci.* **1990**, *13*, 25–42. [CrossRef]
40. Fan, J.; McCandliss, B.D.; Sommer, T.; Raz, A.; Posner, M.I. Testing the Efficiency and Independence of Attentional Networks. *J. Cogn. Neurosci.* **2002**, *14*, 340–347. [CrossRef]
41. Mathôt, S.; Schreij, D.; Theeuwes, J. OpenSesame: An Open-Source, Graphical Experiment Builder for the Social Sciences. *Behav. Res. Methods* **2012**, *44*, 314–324. [CrossRef]
42. Efron, B. Bootstrap Methods: Another Look at the Jackknife. *Ann. Stat.* **1979**, *7*, 1–26. [CrossRef]
43. Rousselet, G.; Pernet, C.; Wilcox, R. An Introduction to the Bootstrap: A Versatile Method to Make Inferences by Using Data-Driven Simulations. Available online: https://files.osf.io/v1/resources/h8ft7/providers/osfstorage/5cebe77123fec40018e6c1f3?format=pdf&action=download&direct&version=5 (accessed on 29 May 2023).
44. Grassini, S.; Revonsuo, A.; Castellotti, S.; Petrizzo, I.; Benedetti, V.; Koivisto, M. Processing of Natural Scenery Is Associated with Lower Attentional and Cognitive Load Compared with Urban Ones. *J. Environ. Psychol.* **2019**, *62*, 1–11. [CrossRef]
45. Crivelli, L.; Palmer, K.; Calandri, I.; Guekht, A.; Beghi, E.; Carroll, W.; Frontera, J.; García-Azorín, D.; Westenberg, E.; Win-kler, A.S.; et al. Changes in cognitive functioning after COVID-19: A systematic review and meta-analysis. *Alzheimer's Dement.* **2022**, *18*, 1047–1066. [CrossRef] [PubMed]
46. Akıncı, B.; Oğul, Ö.E.; Hanoğlu, L.; Kulaç, B.; Ören, D.; Ulu, O.; Basançelebi, B. Evaluation of Cognitive Functions in Adult Individuals with COVID-19. *Neurol. Sci.* **2023**, *44*, 793–802. [CrossRef]
47. Favieri, F.; Forte, G.; Agostini, F.; Giovannoli, J.; Di Pace, E.; Langher, V.; Tambelli, R.; Pazzaglia, M.; Giannini, A.M.; Casagrande, M. The Cognitive Consequences of the COVID-19 Pandemic on Members of the General Population in Italy: A Preliminary Study on Executive Inhibition. *J. Clin. Med.* **2022**, *11*, 170. [CrossRef]
48. Verbruggen, F.; McLaren, I.P.L.; Chambers, C.D. Banishing the Control Homunculi in Studies of Action Control and Behavior Change. *Perspect. Psychol. Sci. J. Assoc. Psychol. Sci.* **2014**, *9*, 497–524. [CrossRef]
49. Benedetti, V.; Gavazzi, G.; Giovannelli, F.; Bravi, R.; Giganti, F.; Minciacchi, D.; Mascalchi, M.; Cincotta, M.; Viggiano, M.P. Mouse Tracking to Explore Motor Inhibition Processes in Go/No-Go and Stop Signal Tasks. *Brain Sci.* **2020**, *10*, 464. [CrossRef]
50. Aron, A.R.; Poldrack, R.A. Cortical and Subcortical Contributions to Stop Signal Response Inhibition: Role of the Subthalamic Nucleus. *J. Neurosci. Off. J. Soc. Neurosci.* **2006**, *26*, 2424–2433. [CrossRef] [PubMed]
51. Gavazzi, G.; Giovannelli, F.; Currò, T.; Mascalchi, M.; Viggiano, M.P. Contiguity of Proactive and Reactive Inhibitory Brain Areas: A Cognitive Model Based on ALE Meta-Analyses. *Brain Imaging Behav.* **2021**, *15*, 2199–2214. [CrossRef]

52. Gavazzi, G.; Giovannelli, F.; Noferini, C.; Cincotta, M.; Cavaliere, C.; Salvatore, M.; Mascalchi, M.; Viggiano, M.P. Subregional Prefrontal Cortex Recruitment as a Function of Inhibitory Demand: An FMRI Metanalysis. *Neurosci. Biobehav. Rev.* **2023**, *152*, 105285. [CrossRef]
53. Braver, T.S. The Variable Nature of Cognitive Control: A Dual Mechanisms Framework. *Trends Cogn. Sci.* **2012**, *16*, 106–113. [CrossRef]
54. Berto, R. Exposure to Restorative Environments Helps Restore Attentional Capacity. *J. Environ. Psychol.* **2005**, *25*, 249–259. [CrossRef]
55. Berman, M.G.; Jonides, J.; Kaplan, S. The Cognitive Benefits of Interacting with Nature. *Psychol. Sci.* **2008**, *19*, 1207–1212. [CrossRef]
56. Hassan, A.; Tao, J.; Li, G.; Jiang, M.; Aii, L.; Zhihui, J.; Zongfang, L.; Qibing, C. Effects of Walking in Bamboo Forest and City Environments on Brainwave Activity in Young Adults. *Evid.-Based Complement. Altern. Med. ECAM* **2018**, *2018*, 9653857. [CrossRef]
57. Pasanen, T.; Johnson, K.; Lee, K.; Korpela, K. Can Nature Walks with Psychological Tasks Improve Mood, Self-Reported Restoration, and Sustained Attention? Results From Two Experimental Field Studies. *Front. Psychol.* **2018**, *9*, 2057. [CrossRef] [PubMed]
58. Kaplan, S.; Berman, M.G. Directed Attention as a Common Resource for Executive Functioning and Self-Regulation. *Perspect. Psychol. Sci. J. Assoc. Psychol. Sci.* **2010**, *5*, 43–57. [CrossRef]
59. Kuo, F.E.; Sullivan, W.C. Environment and Crime in the Inner City: Does Vegetation Reduce Crime? *Environ. Behav.* **2001**, *33*, 343–367. [CrossRef]
60. Weinstein, N.; Przybylski, A.K.; Ryan, R.M. Can Nature Make Us More Caring? Effects of Immersion in Nature on Intrinsic Aspirations and Generosity. *Pers. Soc. Psychol. Bull.* **2009**, *35*, 1315–1329. [CrossRef]
61. Cristillo, V.; Pilotto, A.; Cotti Piccinelli, S.; Zoppi, N.; Bonzi, G.; Gipponi, S.; Sattin, D.; Schiavolin, S.; Raggi, A.; Bezzi, M.; et al. Age and Subtle Cognitive Impairment Are Associated with Long-Term Olfactory Dysfunction after COVID-19 Infection. *J. Am. Geriatr. Soc.* **2021**, *69*, 2778–2780. [CrossRef]
62. Almeria, M.; Cejudo, J.C.; Sotoca, J.; Deus, J.; Krupinski, J. Cognitive Profile Following COVID-19 Infection: Clinical Predictors Leading to Neuropsychological Impairment. *Brain Behav. Immun. Health* **2020**, *9*, 100163. [CrossRef] [PubMed]