CORTEX 162 (2023) 56–64

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Journal homepage: www.elsevier.com/locate/cortex

Single Case Report

Persistent prosopagnosia following COVID-19

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ARTICLE INFO

Article history:
Received 19 June 2022
Reviewed 02 August 2022
Revised 2 November 2022
Accepted 13 January 2023
Action editor Holger Wiese
Published online 9 March 2023

Keywords:
COVID-19
Post-acute sequelae of SARS-CoV-2 infection (PASC)
Prosopagnosia
Face blindness
Case study

ABSTRACT

COVID-19 can cause psychological problems including loss of smell and taste, long-lasting memory, speech, and language impairments, and psychosis. Here, we provide the first report of prosopagnosia following symptoms consistent with COVID-19. Annie is a 28-year-old woman who had normal face recognition prior to contracting COVID-19 in March 2020. Two months later, she noticed face recognition difficulties while experiencing symptom relapses and her deficits with faces have persisted. On two tests of familiar face recognition and two tests of unfamiliar face recognition, Annie showed clear impairments. In contrast, she scored normally on tests assessing face detection, face identity perception, object recognition, scene recognition, and non-visual memory. Navigational deficits frequently co-occur with prosopagnosia, and Annie reports that her navigational abilities are substantially worse than before she became ill. Self-report survey data from 54 respondents with long COVID showed that a majority reported reductions in visual recognition and navigation abilities. In summary, Annie's results indicate that COVID-19 can produce severe and selective neuropsychological impairments similar to deficits seen following brain damage, and it appears that high-level visual impairments are not uncommon in people with long COVID.

1. Introduction

Post-acute sequelae of SARS-CoV-2 infection (PASC), also referred to as long-haul COVID or long COVID, is characterized by a multitude of symptoms that begin, resurface, or persist more than twelve weeks after the initial COVID-19 infection (Nalbandian, 2021). These symptoms often include neurological impairments. One of the first neurological symptoms reported was loss of smell and taste (Mao & Jin, 2020); other neurological issues include difficulty with speech, language impairments (Davis et al., 2021), psychosis (Varatharaj et al., 2020), visual problems (Mao & Jin, 2020; Cyr, Vicidomini, Siu, & Elmann, 2020; Gaber & Eltemamy, 2021), and hallucinations (Davis et al., 2021). However, no selective and persisting visual perception deficits following COVID-19 have been reported to date.

Here, we provide the first report of prosopagnosia following COVID-19. Prosopagnosia is a neurological impairment characterized by severe deficits with facial identity recognition (Damasio, Damasio, & VanHoesen, 1982; Mayer & Rossion, 2007; Barton, 2008). Acquired prosopagnosia results

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https://doi.org/10.1016/j.cortex.2023.01.012

from damage to the occipitotemporal face-processing network (Barton, 2008; Rossion, 2014) and frequently co-occurs with deficits affecting navigation (Corrow et al., 2016; Schmidt, 2015), object recognition (Barton, Albonico, Susilo, Duchaine, & Corrow, 2019), and color perception (Bouvier & Engel, 2006).

Below we provide background about the case reported on here and describe the results from tests assessing her face recognition as well as other perceptual and cognitive abilities. We also report survey data from 54 participants suffering from long COVID/PASC that indicates that visual abilities and navigation are affected in a substantial proportion of them.

2. Methods and results

No part of the study procedures or analysis plans was pre-registered prior to the research being conducted.

We report how we determined our sample sizes, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

For Annie's case report, we decided on a sample size of ten female participants in the same age range as Annie for all tests that we collected control data for. Ten participants seemed a sufficient number given Annie's clear-cut results in the tests; the number of control participants to test was determined after analyzing Annie's data. The sample size for the long COVID/PASC survey group was not determined a priori; the survey got published in a COVID support group and 82 people responded. After excluding all subjects that did not suffer from COVID-19 symptoms for at least 12 weeks, the sample size for the PASC group was $N = 54$. The sample size for the survey control group was set to 30 before data collection because a sample of that size would provide an appropriate comparison group to the PASC sample. Due to an error made by the testable minds testing platform, data from 32 participants were recorded and used in the analyses. Control participants had to have contracted and fully recovered from COVID-19 in the past, and experienced COVID-19 symptoms for less than 12 weeks. These criteria were established prior to data analysis.

Legal copyright restrictions prevent public archiving of Digit Span Test, Verbal Paired Association Memory test, Novel Object Memory Test (Ziggerins), and Abstract Art Memory Test which can be obtained from the copyright holders in the cited references.

All other tests in this study can be accessed in the test repository: https://data.mendeley.com/datasets/css895mcyk/1.

2.1. *Case report Annie*

Annie is a 28-year-old customer service representative and part-time portrait artist who experienced her first symptoms consistent with COVID-19 in March 2020. Symptoms included a 103 °F/39.4 °C fever, coughing fits that led to fainting due to lack of oxygen, tightness in the chest, shortness of breath, diarrhea, and loss of smell and taste. Annie was not hospitalized, not tested for COVID-19 due to lack of tests, but was diagnosed by her primary care provider, and did not go to the Emergency Department (ED) due to concerns about out-of-pocket medical costs. Three weeks after symptom onset, Annie felt well enough to start working from home again. Seven weeks after the onset of her illness many of Annie's symptoms returned, and she noticed disorientation and that "something was off with faces". These deficits caused her primary care provider to send her to seek care in an Emergency Department (ED). At the ED, a CT scan revealed no active bleeds in her brain, and she was discharged.

In June 2020, Annie spent time with her family for the first time since becoming ill with COVID-19 and noticed that she was unable to recognize her father or visually distinguish him from her uncle. She describes the experience as: "My dad's voice came out of a stranger's face." Annie reports that she is now relying heavily on people's voices for identification purposes. While she was previously able to draw a face and only look at a reference photo every 15–30 min, she now depends on photographs while drawing, explaining that "Faces are like water in my head." She equates looking at and then trying to remember faces to viewing a Chinese character without any knowledge of the language and then being asked to reproduce it from memory.

Like many individuals with acquired prosopagnosia, Annie also experiences impairments that affect her ability to navigate in familiar environments (Schmidt, 2015). For example, she has had repeated difficulty finding her way around her grocery store. She reports losing her sense of direction frequently and having to drop a pin on Google maps to be able to find her parked car later. Annie also notes that she now has difficulty telling cardinal directions and is much more likely to find herself driving in the direction opposite to her intended destination.

Annie shows symptoms of PASC, including symptom relapses, fatigue, difficulty concentrating, and brain fog. Starting in November 2020, Annie started to experience balance issues and frequent migraines in addition to the symptoms mentioned above. A neurologist told Annie that a stroke was unlikely to have caused her symptoms. However, an MRI scan was not done due to insurance problems so a stroke cannot be excluded as the cause of her symptoms, especially given the evidence for increased risk of stroke with COVID-19 (Katsoularis, Fonseca-Rodríguez, Farrington, Lindmark, & Connolly, 2021; Fifi & Mocco, 2020). Years prior, Annie was diagnosed with postural orthostatic tachycardia syndrome (POTS) but had not experienced any cardiac or neurological issues before her COVID-19 infection. She briefly took medication for POTS but discontinued it because the condition affects her only mildly.

2.1.1. *General cognitive functioning*

Annie completed behavioral tests remotely on an internet testing platform (testable.org; Rezlescu, Danaila, Miron, & Amariei, 2020) while speaking on the telephone with the first author of this study. These tests were used to assess basic cognitive functioning and object recognition in November 2020, which all revealed normal performance. To assess her verbal episodic memory, Annie was tested with the Verbal Paired Association Memory (VPAM) test (Woolley, Gerbasi, Chabris, Kosslyn, & Hackman, 2008). In this test, participants attempted to learn 25 word pairs (e.g., lamp/tractor), which

were shown together for 6 s each. In the test phase, participants were shown one word from each pair and were asked to select the word it had been paired with from four options. Annie was correct on 18/25 trials (72%, control mean = 50.2%, SD = 20.4%, data from Wilmer et al., 2010, control mean age = 27, SD = 11, N = 1532 (986 female)). Annie scored 80% on a visual memory test with abstract art stimuli (control mean = 66.2%, SD = 12.6%, data from Wilmer et al., 2010, control mean age = 28, SD = 12, N = 3004 (1932 female)) and 81.9% on another test that required recognition of novel objects (NOMT Ziggerins, control mean = 84.4%, SD = 11.2%, data from Richler, Wilmer, & Gauthier, 2017, control mean age = 32.6, SD = 14.1, N = 674 (368 female)). On two measures of verbal short-term memory, Annie scored around the control mean for Forward Digit Span (7 digits repeated without error, control mean = 6.2, SD = 1.14, data from Grégoire & Van der Linden, 1997, control age range = 25–34, N = 100 (50 female)) and well above the control mean on Backward Digit Span (7 digits repeated without error, control mean = 4.71, SD = 1.29, data from Grégoire & Van der Linden, 1997, control age range = 25–34, N = 100 (50 female)) (Wechsler, 1997). Annie's normal performance on these tests indicates that her difficulties with facial identity recognition do not result from broad cognitive deficits.

2.1.2. *Face recognition*

We assessed Annie's face recognition ability with four face identity memory tests (Fig. 1) and analyzed results from these tests with a one-tailed *t*-test from Crawford et al.'s (2010) single-case analysis program Singlims_ES.exe which provides effect size estimates with a 95% confidence interval (CI), and an estimate of proportion of the normal population achieving a lower score than the single case.

First, Annie completed two tests focusing on long-term face recognition: A famous faces test and a doppelganger test. In the famous faces test, participants were shown 60 photographs of celebrities and were asked to name or uniquely identify each person. Annie correctly identified 29.2% of the 48 celebrities she was familiar with whereas controls (mean age = 28.2, SD = 3.1, N = 10 (all female), data collected for this study) identified 83.6% (SD = 10%) of the celebrities they were familiar with (mean familiarity = 47.1 out of 60, SD = 6.4). Annie's score is significantly below the control scores ($t = -5.208$, $P = .00028$, effect size for difference between Annie and controls (+95% confidence interval) = −5.462 (−8.009 to −2.905), and an estimated .03% of the normal population fall under Annie's score).

To determine whether deficits with name recall might have caused Annie's poor performance on the famous faces test, we tested her with a doppelganger test in which participants were presented with 60 test trials in which the name of a famous person was followed by two simultaneously presented photos—one of the famous person and one of a person who closely resembles the celebrity. Participants (mean age = 24.1, SD = 4.1, N = 25 (14 female), data collected for this study) indicated which photo showed the famous person. Annie correctly selected the celebrity photo on 69% of the 58 trials that involved a celebrity who she was familiar with (control mean = 86.7%, SD = 10%, chance = 50%). This percent correct is significantly below the control scores ($t = -1.734$, $P = .049$, effect size (+95% CI) = −1.768 (−2.394 to −1.128), and an estimated 4.8% of the normal population would perform below Annie's score),

Because participants vary in their exposure to famous faces, we next examined Annie's performance on a commonly used test of unfamiliar face recognition. In the Cambridge Face Memory Test (CFMT), participants were introduced to six male target faces sequentially and were then asked to choose which of three simultaneously-presented faces is one of the six target faces (Duchaine & Nakayama, 2006). Annie scored 55.6% correct on the CFMT (Fig. 1, Supplementary Figure 1), which indicates a clear impairment with face recognition ($t = -2.242$, $P = .015$, effect size (+95% CI) = −2.264 (−2.786 to −1.734), and an estimated 1.5% of the normal population fall below Annie's score) when compared to the controls (control

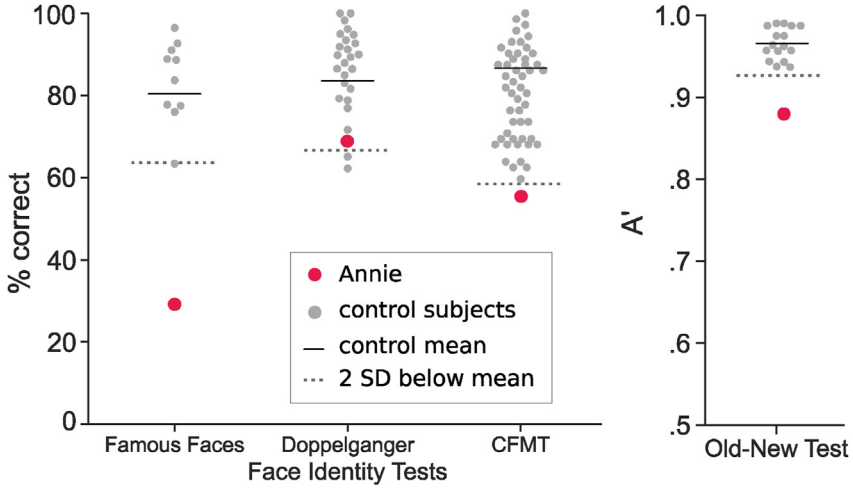

Fig. 1 – Results of face recognition tests. The left panel shows % correct for Famous Faces, Doppelganger, and Cambridge Face Memory Test. The right panel shows A-Prime for the Faces Old–New Test, with values ranging from chance discrimination (.5) to perfect discrimination (1.0). Annie's results are in red; control participant results are gray with a solid black line displaying the control mean. Annie showed impaired performance in all four tests.

mean = 80%, standard deviation = 11%, chance = 33.3%, control mean age = 20.2, SD = 1.8, N = 50 (29 female), from Duchaine & Nakayama, 2006).

Annie then completed an old-new face identity test in which participants were asked to remember ten faces that were each shown twice. Participants were then presented with 50 faces sequentially; 30 faces that were new to them and 20 consisting of two presentations of each of the 10 faces they were asked to learn. Participants indicated whether each face was new to them or was one of the women they were asked to remember. Annie achieved an A-prime of .87 (control mean A' = .96, SD = .02, control mean age = 27.8, range 24–34, N = 17 (9 female), data from Duchaine, Yovel, Butterworth, & Nakayama, 2006), which is significantly below the control participants (t = -4.274, P = .0003, effect size (+95% CI) = −4.406 (−6.034 to −2.764), and an estimated .03% of the normal population falling below Annie's score) (see Fig. 1).

Overall, Annie's performance in the face recognition tests clearly shows an impairment in face recognition that affects short-term and long-term face identity memory.

2.1.3. *Face detection and perception*

To assess whether other aspects of Annie's face processing are impaired, she completed face detection and face identity perception tests. Face detection tasks measure the ability to perceive the presence of a face in a stimulus. Because Annie's detection scores and all other scores reported below are all clearly in the normal range, we do not report the results of Crawford et al.'s (2010) statistical tests.

Annie was tested with a face detection task in which participants were presented with three two-tone (black and white) images simultaneously for 400 ms (Mooney, 1957; Rezlescu, Chapman, Susilo, & Caramazza, 2016). One of the three images contained a face and participants were asked to select it. Thirty-nine trials used upright faces and 39 trials involved upside-down faces. Trials were blocked by orientation. Annie's scores were normal: 74.4% upright (control mean = 80%, SD = 8.8%, data from web sample in Rezlescu et al., 2016, mean age = 36.1, SD = 10.1, N = 63 (27 female)) and 51.3% inverted (control mean = 51.9%, SD = 10.9%, data from web sample in Rezlescu et al., 2016, mean age = 36.1, SD = 10.1, N = 63 (27 female)).

In a face matching test (Duchaine et al., 2006; Rezlescu et al., 2016), participants were presented with a target face for 400 ms and then attempted to choose the matching face from three faces shown simultaneously from a different viewpoint for 2000 ms. Forty trials were upright and 40 upside-down. Annie was correct on 75% of upright (control mean = 78.7%, SD = 11.6%, data from web sample in Rezlescu et al., 2016, mean age = 36.1, SD = 10.1, N = 63 (27 female)) and 40% of inverted trials (control mean = 53.6%, SD = 13.5%, data from web sample in Rezlescu et al., 2016, mean age = 36.1, SD = 10.1, N = 63 (27 female)).

Annie also completed the Cambridge Face Perception Test in which participants were given 40 s on each trial to sort six faces in terms of their similarity to a reference face (Duchaine, Yovel, & Nakayama, 2007). Half the sorts involved upright faces and the other half were inverted faces. Annie achieved 65.2% correct in the upright (control mean = 72%, SD = 10%, chance = 35.6%, data from web sample in Rezlescu, Susilo, Wilmer, & Caramazza, 2017, control mean age = 36.2, SD = 11.5, N = 202 (122 female)) and 45.8% in the inverted condition (control mean = 53%, SD = 10%, data from web sample in Rezlescu et al., 2017, control mean age = 36.2, SD = 11.5, N = 202 (122 female)). Annie's normal scores on face detection and face identity perception tests indicate that her impairments with faces result from memory deficits for faces rather than an impairment in face perception, indicating she is suffering from associative and not apperceptive prosopagnosia.

2.1.4. *Car detection and perception*

To determine whether Annie experiences object recognition impairments, we tested her with a variety of car tasks that use designs identical to face tests described above. In the Cambridge Car Memory Test (Dennett et al., 2012), Annie scored 70.8% correct (control mean = 70.6%, SD = 9.93%, data from Dennett et al., 2012, mean control age = 20.6, SD = 2.9, N = 153 (93 female)). She also performed normally on car versions of the Mooney-style detection test described above (upright: Annie = 89.7%, control mean = 75.1%, SD = 11.7%, inverted: Annie = 64.1%, control mean = 46.7%, SD = 9.7%, data from Rezlescu et al., 2016, mean age = 36.1, SD = 10.1, N = 63 (27 female)) as well as the matching test (upright: Annie = 62.5%, control mean = 76.5%, SD = 10.1%, inverted: Annie = 50%, control mean = 53.2%, SD = 11.1%. Data from Rezlescu et al., 2016, mean age = 36.1, SD = 10.1, N = 63 (27 female)). In an old-new car test, Annie achieved an A-prime of .91 (control mean A' = .94, SD = .03, data from Duchaine et al., 2006, control mean age = 27.8, range 24–34, N = 17 (9 female)). Her performance with cars and normal scores on the two visual recognition tasks used to assess her general cognitive functioning above indicate that Annie's object recognition remains intact.

2.1.5. *Scene processing*

Annie reports problems with navigating her environment that arose after her COVID-19 infection. These problems include confusing cardinal directions, being unable to find her car in a parking lot, and difficulty finding the sections with milk or bread in a grocery store that she visits often. To examine whether Annie's navigational difficulties could be due to a disruption in visual scene processing, we examined her performance with old-new tests requiring recognition of houses (control mean A' = .97, SD = .03, data from Duchaine et al., 2006, control mean age = 27.8, range 24–34, N = 17 (9 female)) and natural scenes (control mean A' = .97, SD = .03, data from Duchaine et al., 2006, control mean age = 27.8, range 24–34, N = 17 (9 female)). On both tests, Annie made no errors, achieving an A-prime of 1 in each test. These results indicate that Annie is capable of recognizing places normally and thus suggest that her navigational impairments result from later processes that contribute to cognitive map representation (Aguirre & D'Esposito, 1999).

2.1.6. *Voice processing*

Deficits with facial identity recognition can be caused by multimodal identity impairments outside the visual system (Gainotti, 2013; Liu, Pancaroglu, Hills, Duchaine, & Barton, 2016), but Annie believes she is still able to recognize people by their voice. To formally assess her voice recognition, we

used a voice test that introduces six female speakers by name to participants (Garrido et al., 2009, Jiahui, Yang, & Duchaine, 2018). Over three blocks, participants were presented with a speaker's name, heard a speaker saying a sentence, and then indicated whether the name and speaker are consistent. Annie's performance across the three blocks was around average to above average (Fig. 2). After the first three test blocks, recognition trials were presented in which sentences were spoken and participants selected which of the six speakers said the sentence. Annie's score was above average (Fig. 2). Lastly, Annie did a voice old/new test in which the participants were asked to indicate if the person speaking is one of the six speakers they were familiarized with or a new person. On this test, Annie again scored better than the control average (control mean age = 26.4, SD = 2.8, N = 10 (4 female, data collected online on testable.org for this study). Annie's normal voice performance indicates her face identity deficits result from disruptions within the visual system.

2.2. COVID-19 survey

Annie's report and test results raise the question of whether perception, recognition, and navigational problems also affect other people who have contracted COVID-19. To assess this possibility, we surveyed two groups of individuals who had contracted COVID-19. One group met the criteria for PASC/long COVID (PASC group) because they had symptoms for 12 weeks or more (N = 54, ages 22–74, mean = 45.1, SD = 11.3, 91% Caucasian, 83% female, 85.2% right-handed, days experiencing COVID symptoms: 100–292 days, mean = 195.2, SD = 46.2, median = 210). Respondents in the PASC group had been diagnosed with COVID-19 by a clinician (75.9%), PCR test (7.4%), antibody test (3.7%), or self-diagnosed (13%). 14.8% of the PASC group reported experiencing mild symptoms, 64.8% moderate symptoms, and 20.4% severe symptoms. Two participants reported hospitalizations, but neither were treated with a ventilator. Respondents in the control group (N = 32, ages 21–59, mean = 39.2, SD = 10.3, 78.1% Caucasian, 46.9% female, 84.4% right-handed, days experiencing COVID symptoms: 3–75 days, mean = 11.7, SD = 12.6, median = 9.5) had been diagnosed with COVID-19 by a clinician (25%), PCR test (62.5%), antibody test (9.4%), or self-diagnosed (3.1%), and stated that they had recovered fully from their COVID-19 infection. 43.75% reported having mild symptoms, 56.25% moderate symptoms, and none reported severe symptoms or hospitalization.

The survey contained 17 statements about visual perception and cognitive functioning that the participants were asked to self-report and rate on a 5-point Likert scale from "Completely agree" to "Completely disagree" once for the time before they had contracted COVID-19, and once for the period after they had mostly recovered from COVID-19. A full list of questions can be found in the supplementary materials. Annie is not included in the PASC group because she did not respond to the survey.

Likert scale answers were converted to numerical values (Norman, 2010), inverted for negative questions, and a paired t-test with Bonferroni correction between ratings before and after COVID-19 infections was performed for each question, per survey group. Data from the PASC group showed a significant drop for twelve out of 17 questions between participants' before COVID-19 and after COVID-19 ratings (see Supplementary Table 1). In contrast, the control group reported no significant differences before and after their COVID-19 infection (see Supplementary Table 1). Fig. 3 shows examples of averaged before and after ratings for object recognition and navigation in the PASC group. Supplementary Figures 2 and 3 show averages for all questions per group.

Respondents in the PASC group also reported being less capable of navigating their environment after recovering from COVID-19 (see Fig. 3B). Interestingly, several participants in the PASC group noticed reduced color perception but this difference did not reach significance (see Supplementary Table 1; Supplementary Figures 2 and 4).

When comparing the changes between the self-reported ratings before and after their COVID-19 infection across the

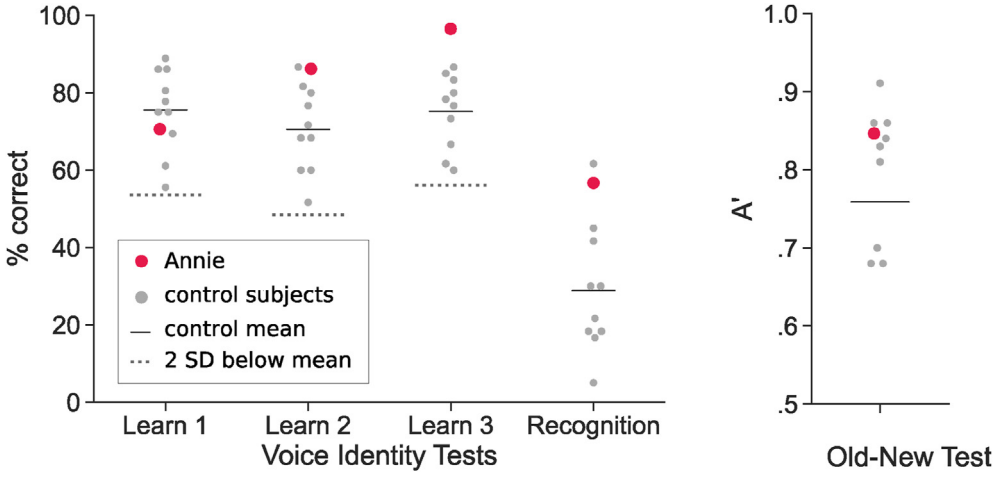

Fig. 2 – Results of voice recognition tests. The left panel shows percent correct for learning of six female voices and a voice recognition test. The right panel shows A-Prime for the Voice Old–New Test, with values ranging from chance discrimination (.5) to perfect discrimination (1.0). Annie's results are in red; control participant results are gray with a solid black line displaying the control mean. Annie shows normal to above-normal voice processing capability in all five tests.

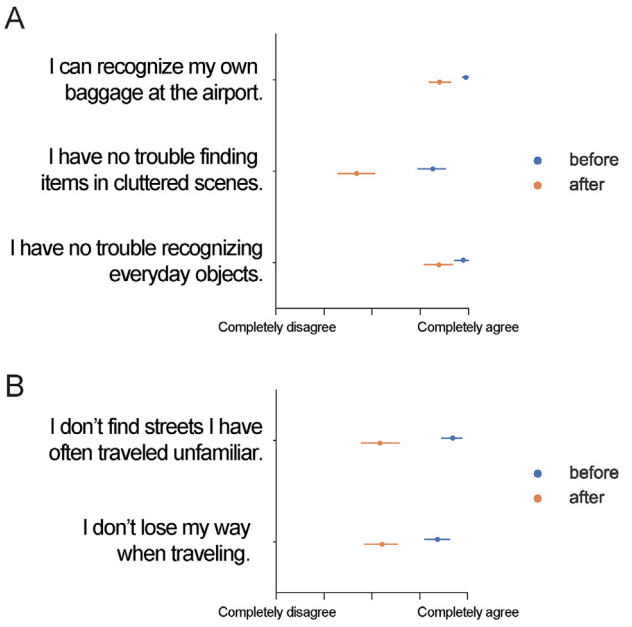

Fig. 3 – PASC group mean scores on Likert-scale for A) Object recognition and B) Navigation questions from the survey. X-axis shows answer options on Likert scale from "Completely disagree" to "Completely agree". Error bars indicate 95% confidence interval.

groups with a Welch's t-test (Welch, 1947), significant differences between the groups were found for seven of the 17 questions. Compared to the survey control group, respondents in the PASC group reported a significantly larger decrease in their abilities to track characters on TV, navigate their environment, find items in a cluttered scene, remember a phone number, as well as understanding speech, and reading (see Supplementary Table 2).

To explore whether the change in the ratings before and after COVID-19 in the PASC group were driven by pronounced differences in a small number of participants or by a substantial number of participants reporting more modest changes, we computed the difference between the before and after ratings for each participant (deltas). These deltas were then plotted in a count plot. Fig. 4 shows deltas for two navigation questions, six face processing questions, and three object processing questions in the PASC group (see Supplementary Figures 2 and 4 for results in the PASC group for all questions; Supplementary Figures 3 and 5 for controls). Participants in the PASC group reported significant differences for two of the six face processing questions: difficulty keeping track of TV characters, as well as visualizing the faces of close friends or family. For the face visualizing question, the majority of participants reported no difference before and after COVID-19, responses were more broadly distributed for keeping track of TV characters. Differences for questions about navigation and object processing also showed greater spread across participants. Overall, the driving factor for significant differences in ratings before and after COVID-19 in the PASC group seems to be a fair number of participants reporting varying degrees of reduced performance rather than a few participants with dramatic drops.

3. Discussion

COVID-19 can produce long-term neurological impairments such as loss of smell and taste (Mao & Jin, 2020), memory problems and brain fog (Davis et al., 2021), verbal memory deficits, difficulty processing spoken language, and visuospatial memory problems (Ferrucci et al., 2021). Problems with visual perception were mentioned in Mao and Jin (2020), and Graham et al. (2021) reported that 18.4% of their participants suffered from problems with visual long-term memory but no previous studies have shown severe, selective effects to visual processing caused by COVID-19.

In this article, we presented data from Annie, a 28-year-old woman, who is suffering from face recognition and navigational difficulties in daily life after being ill with what appeared to be COVID-19 and suffering from long COVID/PASC. We formally assessed her face recognition ability by testing her with four tests: a famous faces test and a Doppelganger test to assess her long-term face identity recognition abilities, and two tests of unfamiliar face identity recognition. Consistent with her difficulties with face recognition in daily life, Annie performed poorly on all four tests. Her normal scores on face identity perception and face detection tasks indicate that her difficulties with faces specifically involve face memory processes. In contrast to her face deficits, Annie shows no impairment with object recognition. She also does not show other cognitive impairments or significant general memory problems. Her intact face perception abilities indicate that Annie suffers from an associative form of prosopagnosia and brings up the question of whether her identity processing deficits are multimodal. Annie's normal voice recognition performance, however, demonstrates that her person identity recognition impairments are not multimodal but are instead limited to the visual domain. Like a substantial proportion of cases with acquired prosopagnosia (Schmidt, 2015), Annie experiences difficulty navigating familiar environments. The co-occurrence of prosopagnosia and navigational difficulties likely arises due to the proximity of brain regions critical for scene and face processing (Corrow et al., 2016). Overall, due to the dissociations between Annie's face memory deficits but intact object and scene processing, the results indicate that Annie's visual recognition deficits are face specific. While Annie's neuropsychological impairments could be the consequence of an independent problem that co-occurred at the roughly same time as her COVID-19 infection, we believe it is much more likely that Annie's prosopagnosia and navigational deficits were caused by COVID-19 or long COVID/PASC because of the close temporal link between the onset of her problems and her COVID-19 infection.

To investigate whether other people who had COVID-19 also experience perceptual and specific cognitive deficits, we asked individuals who have had symptoms for more than 84 days (PASC group) as well as those who had recovered from COVID-19 (control group) to respond to a survey. In this survey, participants self-reported on their abilities to perform a variety of tasks before and after their COVID-19 infection. While the control group of fully recovered participants did not show significant differences between before and after, participants in the PASC group reported significant decreases in

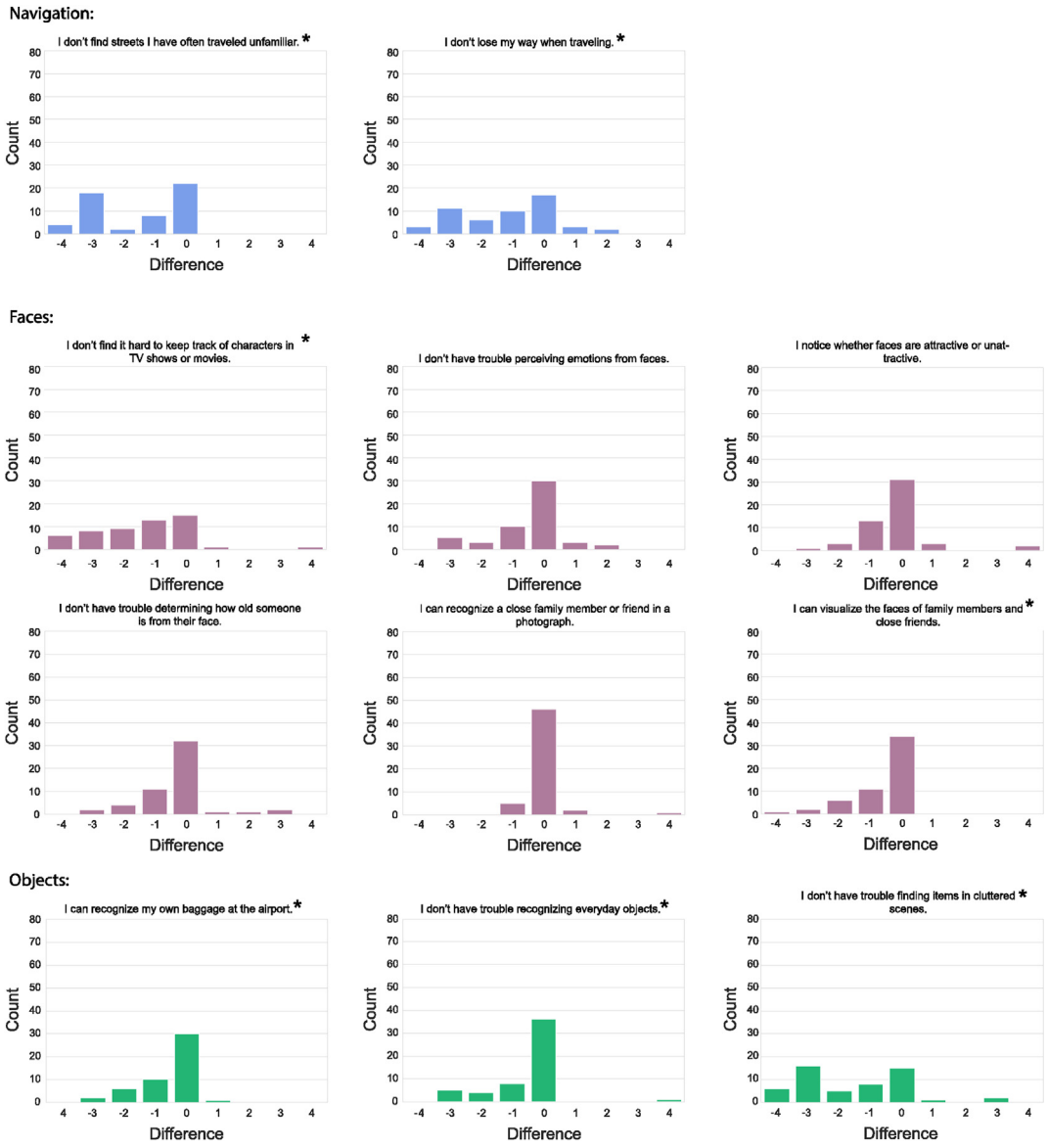

Fig. 4 – Differences between PASC group participants' ratings for tasks relating to navigation (top, blue), faces (middle, purple), and objects (bottom, green) before contracting and after recovering from COVID-19. X-axes show difference value (i.e. delta), Y-axes display number of people who showed a particular delta per question. Questions with significant difference before and after COVID-19 are marked with an asterisk. We suspect that many of the differences indicating large improvements after COVID-19 resulted from response errors.

their ability to perform several tasks including identifying people and objects, voice recognition, memorizing phone numbers, and reading comprehension. A substantial proportion of survey respondents also reported difficulty navigating their environment after their COVID-19 infection. Davis et al. (2021) asked a question about navigation in a survey of participants with PASC/long COVID and found that 20% of the participants reported difficulty finding their way home. We found that 32.9% of our participants in the PASC group report getting lost when traveling after COVID-19 as opposed to 9.6% prior to their COVID-19 illness, and 45.6% find familiar streets unfamiliar after COVID-19 compared to 7.4% before contracting COVID-19.

Brain fog, also referred to as mental fatigue, is one of the most common symptoms in people with long COVID (Goërtz et al., 2020; Graham et al., 2021; Komaroff & Bateman, 2021). Brain fog is characterized by the inability to concentrate, memory problems (Ross, Medow, Rowe, & Stewart, 2013), and not being able to process multiple inputs (Callan, Ladds, Husain, Pattinson, & Greenhalgh, 2022). Given these effects, we considered the role that brain fog might play in Annie's deficits with faces and navigation and in the changes in the ratings of our survey respondents. In Annie's case, it is unlikely that brain fog caused her impairment with face identity recognition because she achieved normal scores in object recognition tests and voice identity recognition tests that are matched to the face tests in task demands and difficulty. As for the survey respondents, brain fog seems likely to play a role in the difficulties the participants in the PASC group are describing. However, brain fog seems an unlikely explanation

for the reductions in color perception reported by 32.1% of participants in the survey. These changes suggest that Annie may be one of many people with long COVID/PASC who have sustained damage to the visual system. Consistent with this view, studies measuring the co-occurrence of chronic fatigue syndrome (CFS) and face processing difficulties did not find significant differences between groups of participants with and without chronic fatigue syndrome (Cope, Pernet, Kendall, & David, 1995, review on CFS and cognitive dysfunctions: Teodoro, Edwards, & Isaacs, 2018).

Previous studies of the long-term effects of COVID-19 have reported deficits in memory, attention, and concentration that substantially impair everyday functioning (Davis et al., 2021). Here we report that, in addition to the well-known broad impairments, COVID-19 sometimes causes severe selective impairments like prosopagnosia. Survey data we collected from individuals with PASC/long COVID also showed that perceptual and cognitive deficits following COVID-19 were present in a substantial proportion of the respondents, though none report having acquired prosopagnosia. Our findings suggest that there are a substantial number of individuals with PASC/long COVID who are experiencing selective visual deficits and indicate that future work should aim to understand the nature of these deficits and whether interventions can be developed that reduce their impact.

Open practices section

The study in this article earned Open Data badge for transparent practices. The data for this study are available at: https://data.mendeley.com/datasets/k48bgntcg5 and https://data.mendeley.com/datasets/css895mcyk/1.

Author Contribution Statement

Marie-Luise Kieseler: Conceptualization, Methodology, Software, Formal analysis, Investigation, Validation, Writing – original draft, Visualization, Brad Duchaine: Conceptualization, Writing – review & editing, Supervision, Validation

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2023.01.012.

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