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Corrigendum: Sensorless wavefront correction in two-photon microscopy across different turbidity scales

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A Corrigendum on
Sensorless wavefront correction in two-photon microscopy across different turbidity scales

by Sohmen M, May MA, Barré N, Ritsch-Marte M and Jesacher A (2022). Front. Phys. 10:884053. doi: 10.3389/fphy.2022.884053

Incorrect definition

We recently presented a study on sensorless wavefront correction across different turbidity scales [1]. In Section 2 of the published article ("*Quantifying turbidity*"), there was an error in Eq. 2. Instead of e^{-L/l_t} (incorrect), where l_t denotes the radiation transport mean free path, it should have read e^{-L/l_s}, where l_s is the scattering mean free path (cf., e.g., Ref. [2–4]). This misnomer carries through Section 2 and reappears, in particular, in Eq. 3, where on the left-hand side L/l_t (incorrect) needs to be replaced by L/l_s.

Accordingly, in the following Sections 3, 4.3, and 4.4, all instances of l_t, "transport mean free path" (incorrect) need to be replaced by l_s, "scattering mean free path", respectively.

However, we note that, fortunately, our incorrect definition does not impact the observed (relative) differences between the two adaptive-optics algorithms or between the three turbidity levels, and hence does not change the conclusions. Below, we present an adapted version of the manuscript Section 2, as well as the corrected sentences in Sections 3, 4.3, and 4.4.

Corrected section 2

It is essential for the present work to define what we mean when speaking of "low" or "high" turbidity. The scattering properties of materials and tissues are often quantified using the scattering mean free path l_s, i.e., the expectation value of a photon's free travelling path before it is scattered. This is mirrored in the Beer-Lambert law, $|U_0(L)|^2 = |U_0(0)|^2\ \mathrm{e}^{-L/l_s}$, where $|U_0(L)|^2$ represents the intensity of the *unscattered* ("ballistic") light after travelling (under free-space propagation) to distance L, and $|U_0(0)|^2$ the incident light intensity. The transport mean free path l_t takes scattering anisotropy into account: $l_t = l_s/(1-g)$, where $g = \langle \cos\theta \rangle$ is the expectation value of the cosine of the scattering angle θ. For instance, in a material which predominantly scatters into the forward direction (causing small scattering angles), l_t is much larger than l_s. Conversely, in an isotropic scatterer $l_t = l_s$. Typical values of l_s for brain tissue range between a few tens to hundreds of micrometers [5–7].

Our goal is to model the effect of a (in general *three-dimensional*, 3D) scattering medium on a light field propagating in positive z-direction by a *two-dimensional* (2D) phase mask, located at axial position $z = z_{\mathrm{scat}}$, with transmission function $\exp(\mathrm{i}\Phi(\boldsymbol{\rho}))$. Here, $\Phi(\boldsymbol{\rho})$ denotes the scattering-related phase shifts experienced by a field point at the 2D lateral coordinate $\boldsymbol{\rho}$. The field after the phase mask is denoted by $U_{\mathrm{scat}}(\boldsymbol{\rho})$. Note that this is the full field, not just a "scattered field" amplitude. Assuming that the phase mask is suitably chosen to describe a medium with predominantly forward scattering and without absorption, we choose the normalisation $\int |U_{\mathrm{scat}}(\boldsymbol{\rho})|^2\ \mathrm{d}\boldsymbol{\rho} = 1 = \int |U_0(\boldsymbol{\rho})|^2\ \mathrm{d}\boldsymbol{\rho}$.

The ballistic contribution at depth L inside the medium—emulated by the phase mask on the SLM—can be calculated using the overlap integral (OI)

$$\mathrm{OI}[U_{\mathrm{scat}}, U_0] = \left| \int U_{\mathrm{scat}}(\boldsymbol{\rho})\ U_0^*(\boldsymbol{\rho})\ \mathrm{d}\boldsymbol{\rho} \right|^2 = \left| \int |U_0(\boldsymbol{\rho})|^2 \mathrm{e}^{\mathrm{i}\Phi(\boldsymbol{\rho})}\ \mathrm{d}\boldsymbol{\rho} \right|^2, \tag{1}$$

i.e., the "projection" of the field with imprinted phase mask onto the unscattered (incident) field. This equality (Eq. 1) is most intuitive if the integral is evaluated in the plane of the 2D scattering mask, but for freely propagated fields the OI in fact stays constant in all transverse planes at $z \geq z_{\mathrm{scat}}$. Using the Lambert-Beer law, the OI can also be written as

$$\mathrm{OI}[U_0(L), U_0(0)] = \mathrm{e}^{-L/l_s}. \tag{2}$$

l_s appears here, since every single scattering event reduces the ballistic contribution. Note that this relation (Eq. 2) implicitly assumes that cases of successive scattering events which exactly compensate each other (thus, re-populating the forward-directed incident field, i.e., contributing to the OI and—erroneously—to the estimated ballistic part) are statistically unlikely and can be ignored.

Combining Eqs 1, 2 we can quantify a computed phase mask in terms of the corresponding "thickness" expressed in units of the scattering mean free path l_s:[1]

$$L/l_s = -\ln(\mathrm{OI}) = -\ln\left(\left| \int |U_0(\boldsymbol{\rho})|^2 \mathrm{e}^{\mathrm{i}\Phi(\boldsymbol{\rho})}\ \mathrm{d}\boldsymbol{\rho} \right|^2 \right) \tag{3}$$

For the case of dominant forward scattering and negligible absorption, this relation allows us to compute a 2D phase mask $\Phi(\boldsymbol{\rho})$ that leads to a speckle pattern in the object plane which is in many ways similar to that of a voluminous 3D scatter medium of the same scattering mean free path l_s. In the experiments described later in this work, we will exploit this fact to simulate different regimes of turbidity by displaying computed 2D scatter masks of specific l_s on an SLM. Of course the equivalence between a 3D and a 2D scatterer—even if they exhibit the same l_s—does not encompass all physical properties; for instance, the isoplanatic patch (i.e., the "corrected field of view") obtained through an AO wavefront correction will be smaller for a 3D than for a 2D scatterer. However, concerning the aspects studied in this work (e.g., the algorithm convergence at a single field point), a 3D and a 2D scatterer of same l_s can be regarded as equivalent.

We denote the RMS value of a scattering phase mask by a_{scat} (see Algorithm 4, Supplementary Material). If the phase values of the mask are normal-distributed or, for any distribution, if a_{scat} is sufficiently small [2], the relation between the scatterer thickness and a_{scat} is simply $L/l_s = \sqrt{a_{\mathrm{scat}}}$.

1 We note that the relation (Eq. 3) is consistent with the considerations made in Ref. [2] (see Eq. 4 therein), which lead to the derivation of the scattering-phase theorem.

Section 3

The corrected sentence should read as:

"It is important to note that this particular case does not necessarily coincide with low turbidity (i.e., a small value of L/l_s), since a large number of modes, even if their individual magnitudes are small, can still sum up to a large total aberration."

Section 4.3

The corrected sentence in the main text should read as:

"First, by displaying a "scattering" phase mask of defined scattering mean free path l_s (see Section 2) it allows to emulate the effect of a scattering medium in the light path."

The corrected sentence in the caption of **Figure 4** should read as:

"The three scenarios A–C correspond to an increasing degree of scattering with (A) $L/l_s = 1$, $\sigma = 1$, (B) $L/l_s = 3$, $\sigma = 3$, and (C) $L/l_s = 5$, $\sigma = 5$, respectively."

Section 4.4

The corrected sentences in the main text should read as:

"In Scenario A we study low turbidity, with an effective scatterer thickness of a single scattering mean free path, $L/l_s = 1$, and a spatial frequency distribution of the scatterer chosen accordingly narrow, $\sigma = 1$."

"In Scenario B, we assume medium turbidity with $L/l_s = 3$ and an intermediate contribution of modes of higher spatial frequency, $\sigma = 3$."

"In Scenario C, we assume high turbidity, with $L/l_s = 5$ and $\sigma = 5$, where without correction typical Strehl ratios are on the order of 1 %."

The authors apologize for these errors and state that this does not change the scientific conclusions of the article in any way. The original article has been updated.

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