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Promise and challenges for discovering transcranial magnetic stimulation induced “numbsense”—Commentary on Ro & Koenig (2021)

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ABSTRACT

The notion that behavioral responses to stimuli can be mediated by separate unconscious and conscious sensory pathways remains popular, but also hotly debated. Recently, Ro and Koenig (2021) reported that when activity in somatosensory cortex was interfered with transcranial magnetic stimulation (TMS), participants could discriminate tactile stimuli they reported not consciously feeling. The study launches an interesting new area of research, helping to uncover mechanisms of unconscious perception that possibly generalize across different sensory modalities. However, we argue here that the study by Ro and Koenig also has several significant shortcomings, and it fails to provide evidence that pathways bypassing primary somatosensory cortex enable unconscious tactile discrimination. By referring to numerous studies investigating TMS-induced blindsight, we outline challenges in demonstrating unconscious sensory pathways using TMS. By facing to these challenges, research investigating TMS-induced numbsense has potential to stimulate progress in stubborn debates and reveal modality-general mechanisms of unconscious perception.

1. Introduction

Patients who have a lesion in one of their primary sensory cortices can sometimes still process stimuli of that sensory domain even though their conscious perception is severely degraded or even eliminated. The most famous example of this is *blindsight*, which suggests an ability to unconsciously perceive visual stimuli despite the primary visual cortex (V1) lesion (Covey, 2010; Pöppel, Held, & Frost, 1973; Weiskrantz, Warrington, Sanders, & Marshall, 1974). A similar phenomenon called *numbsense* has been observed with primary somatosensory cortex (S1) lesions (Paillard, Michel, & Stelmach, 1983; Rossetti, Rode, Rode, & Boisson, 1995). Also in the auditory domain, unconscious processing seems to be possible without the primary sensory cortex: *deafhearing* was reported on a patient with bilateral auditory cortex lesion (Garde & Covey, 2000). The converging evidence from different modalities suggest that unconscious perception may rely on similar neural architecture across different sensory domains.

Whether unconscious processing of sensory information without primary sensory areas is an innate capacity found also in healthy individuals has been debated (Railo & Hurme, 2021). This question has been studied by disturbing the sensory cortical functioning of the healthy participants using transcranial magnetic stimulation (TMS). While previous research has focused on the visual domain, a

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recent study claimed to demonstrate “TMS-induced numbsense”: that pathways bypassing primary somatosensory cortex (S1) can support unconscious tactile discrimination (Ro & Koenig, 2021). The present paper is a commentary on the Ro and Koenig (2021) study. We show that the result Ro and Koenig report is fully consistent with an opposite interpretation: that discrimination was based on degraded conscious perception relying on the primary somatosensory cortex.

The paper by Ro and Koenig is important as it essentially launches a new area of research, helping understand whether sensory cortex bypassing projections constitute a shared architecture that can support unconscious perception in different sensory modalities. We assume and hope this approach of studying unconscious tactile processing is going to get the attention of researchers studying the somatosensory system, and unconscious perception more generally. However, despite the innovative nature of Ro and Koenig’s study, it is also fraught with problems and limitations which the authors fail to mention in the original publication. Many of these issues are not specific to Ro and Koenig (2021) but apply to TMS studies of unconscious perception generally. We will next discuss methodological and theoretical challenges facing research on TMS-induced numbsense using the more widely studied phenomenon of (TMS-induced) blindsight as a reference point.

2. Challenges in demonstrating unconscious pathways

2.1. Unconscious processing or degraded conscious perception?

A central debate in blindsight literature concerns whether blindsight really reveals unconscious perception, or rather, heavily degraded conscious perception (Campion, Latto, & Smith, 1983; Michel & Lau, 2021; Phillips, 2020, 2021). This debate, which Ro and Koenig fail to discuss, generalizes directly to numbsense.

To demonstrate unconscious perception, researchers are faced with the difficult task of measuring subjective conscious perception. To this end, Ro and Koenig asked participants to report on a yes/no scale whether they felt a tactile stimulus. Problematically, such binary scales lead participants to categorize weak conscious percepts erroneously as “unconscious” (Ramsøy & Overgaard, 2004). Consider an analogy: Alien scientists measure the height of humans using a 50 cm long reference stick. As a result, they observe that many of the newborn babies (those under 50 cm) have no height at all and conclude that human mothers sometimes give birth to non-existing babies! It should be obvious why the aliens’ reasoning is flawed. However, by relying on a binary detection scale, Ro and Koenig are essentially making the same fallacy.

Compared to a binary report-scale, a better approach would be to use a scale with several alternatives (Ramsøy & Overgaard, 2004), or a paradigm that minimizes the need to set specific response criteria (Peters & Lau, 2015). Use of graded rating scales does not mean that unconscious perception would not be observed. For example, despite operationalizing “unconscious” as the lowest alternative on a graded rating scale, both Christensen et al. (2008) and Railo and Koivisto (2012) observed that participants could process the location of a visual stimulus that they reported not seeing due to early visual cortex TMS. However, binary scales may lead researchers to mistake response biases for unconscious perception (Lloyd, Abrahamyan, & Harris, 2013; Mazzi, Bagattini, & Savazzi, 2016; Overgaard, Fehl, Mouridsen, Bergholt, & Cleeremans, 2008).

To test how the use of different rating scales influence responding in a TMS-induced blindsight task, Koivisto et al. (2021) directly compared binary and four-alternative rating scales. The results showed that when unconscious perception was defined as the lowest alternative on the four-step scale, participants were at chance in discriminating the orientation of a visual stimulus. In contrast, when a dichotomous scale was used, the participants revealed “unconscious” TMS-induced blindsight: orientation discrimination performance was above chance despite reported unawareness. In other words, the results depended on the rating scale used to measure conscious perception. Yet, the results also suggested that the putative unconscious TMS-induced blindsight (observed with the binary scale) was not truly unconscious vision: Signal detection metrics indicated that across participants, the participant’s sensitivity to *consciously* discriminate orientation predicted behaviour on reportedly unconscious trials (see, (Railo, Piccin, & Lukasik, 2021) for a similar result without TMS). This strongly suggests that TMS-induced blindsight was not truly unconscious but a by-product of a crude rating scale.

Ro and Koenig (2021) used signal detection theoretic measures of sensitivity and criterion (c) to examine whether their result was influenced by a response bias, yet how they interpret these findings is misleading. Ro and Koenig (2021) emphasize that “There was no difference in c values between the TMS trials and the no-TMS trials, $t(11) = 1.83, p > .05$, Cohen’s $d = 0.8$ ” (p. 4). However, while not “statistically significant”, the size of the effect is substantial, suggesting that participants were more inclined to categorize their percepts as “not felt” during TMS. In fact, if one only considers the effect sizes, the difference in response criterion (between TMS and non-TMS trials; Cohen’s $d = 0.8$) is larger than the “unconscious TMS-induced numbsense” the authors report (Cohen’s $d = 0.73$). A more direct test for the possibility that reportedly unconscious discrimination was based on conscious signals would have been to examine if conscious sensitivity or criterion predict reportedly unconscious discrimination, and whether performance on unconscious trials is above-chance level if sensitivity and criterion are close to zero (e.g., as in Koivisto et al., 2021). Unfortunately, when queried, Ro and Koenig were not ready to share their data so that we could have examined for this possibility.

The truth about unconscious perception and criterion is likely to be more complex than either “unconscious pathway” or “degraded conscious” frameworks alone suggest. For example, while criterion level may purely reflect responding, it could also modulate perception (Michel & Lau, 2021; Witt, Taylor, Sugovic, & Wixted, 2015). Moreover, while there are good scientific grounds to argue that participants may be weakly conscious of stimuli they label as “unconscious”, one should be careful not to override the patients’ subjective experience with this. Multiple authors working with patients have stressed that the patients behave in a way that suggests that they really feel that they do not consciously notice the stimulus at hand. It is arguably not helpful for the patient if a scientist asserts her that “statistically speaking, you actually are basing your responses on conscious perception!”. The *practically* interesting question from the perspective of patients is why they report that they do not perceive the stimulus. What would be required that the

patient would “metacognitively” appreciate that she can process the stimulus to a certain degree?

Limited conscious perception or “feelings” about the stimuli may remain despite the primary cortical damage (Ffytche & Zeki, 2011), and it is encouraging that patients with lesions to sensory areas often do improve their perception through rehabilitation (Ajina, Jünemann, Sahraie, & Bridge, 2021; Saionz, Tadin, Melnick, & Huxlin, 2020). Consider the numbsense patient M.St. When asked to point out which location on her impaired hand was just stimulated, she initially says “I don’t feel anything and yet I go there with my finger”. She then learns to tenuously consciously detect the stimulation “as an event” on her impaired hand, and reports using this in localizing the stimulus (p. 549–550; Paillard et al., 1983). What neural mechanism mediates this type of learning? Does it involve changes in stimulus-evoked activation, or is it associated with fine-tuned criterion location (see, Ko & Lau, 2012)? Answers to these questions could prove important for rehabilitation of cortical sensory deficits.

The take home message here is that one should be sensitive to the limitations and complexities surrounding the use of objective, empirical methods to assess subjective conscious perception. While we assume that unconscious processing of stimulus presence may be possible in numbsense, Ro and Koenig’s study fail to provide convincing evidence for it. Next, we turn to the question whether the result reported by Ro and Koenig (2021) demonstrate pathways that bypass S1.

2.2. When and where to stimulate?

Ro and Koenig (2021) argue that their results “implicate a parallel somatosensory pathway that processes the location of touch in the absence of awareness” (abstract). Yet, the actual evidence for S1-bypassing pathways is rather weak. The reasoning that the results support the existence of S1-bypassing pathways relies on the premise that the TMS pulses successfully eliminate *all* tactile-evoked activity in S1. Given that Ro and Koenig (2021) applied TMS pulses before the onset of the tactile stimulus, and did not target TMS based on functional brain imaging, it is likely that they did not eliminate evoked responses in S1.

TMS-induced blindsight suggests that unconscious perception may rely on the initial “feedforward” activation through a primary sensory area (Hurme et al., 2017) providing causal evidence that unconscious perception may depend on the primary sensory cortex, but only at specific time-windows. Similar to conscious vision (Amassian et al., 1989), also tactile perception can be suppressed by TMS to S1 in different time windows. Most effective TMS seems to be from 90 ms before the stimulus to 20 ms after the stimulus, but measurable effects can be found from 200 ms before to 200 ms after the stimulus (Andre-Obadia, Garcia-Larrea, Garassus, & Mau-guiere, 1999; Cohen, Bandinelli, Sato, Kufta, & Hallett, 1991; Seyal, Masuoka, & Browne, 1992). It is reasonable to assume that TMS applied at different time-windows will interfere with different neural processes in the somatosensory cortex. Ro and Koenig (2021) applied TMS 40 ms before the stimulus onset. Arguably, prestimulus TMS may not be sufficient to eliminate the consequent stimulus-evoked activation. This means that the claim that somatosensory cortex did not mediate numbsense-like behavior is unfounded. A more convincing demonstration would include direct comparison between multiple stimulus onset asynchronies (including TMS pulses after stimulus onset) (see e.g. Allen et al., 2020; Center, Knight, Fabiani, Gratton, & Beck, 2019).

In addition to the timing of the pulses, the anatomical site of stimulation can obviously also influence the results. Ro and Koenig (Ro & Koenig, 2021) went with what is known as the hunting method in determining the site of stimulation. In this method you use trial-and-error to find the location that gives you the best suppression of conscious perception. The downside is that TMS may not have been targeted to S1 specifically, meaning that this area may have still contributed to behavior, and suppression of conscious tactile processing could have been mediated by other regions than S1 (Fig. 1 in Ro and Koenig (2021) suggests TMS was more caudal than where S1 is based on brain imaging; Holmes et al., 2019). In visual domain, you can interfere with conscious perception with TMS to V1 but also with TMS to V2 (Salminen-Vaparanta, Koivisto, Noreika, Vanni, & Revonsuo, 2012; Thielscher, Reichenbach, Urbil, & Uluda, 2010) and V3 (Salminen-Vaparanta, Koivisto, Vorobyev, Alakurtti, & Revonsuo, 2019; Thielscher et al., 2010).

Even if TMS pulses are targeted based on neuronavigation, and the pulses interfere with perceptual performance, it is difficult to rule out the possibility that the targeted cortical area contributes to behavior. It could simply be that the conscious processing is just easier to suppress than unconscious processing using TMS. That is, residual activity in the targeted location may not be sufficient to produce conscious perception, but it could nevertheless support unconscious processing. In this case TMS-induced numbsense might be truly unconscious, but not independent projections through the S1.

3. Conclusions

The study by Ro and Koenig (2021) expands the research on TMS-induced unconscious processing of sensory stimuli to other modalities than vision, which enables investigating the neural mechanisms of unconscious processing across different sensory modalities. This has significant promise for elucidating neural correlates of consciousness because it could potentially point towards specific neural architectures that have the potential to enable conscious experience. Comparisons of what types of tasks can be supported by unconscious processing (and specific neural mechanisms) could help understand the function of consciousness: what types of behaviors require conscious perception? For example, TMS studies within the visual domain suggest that localization or detection of the presence of stimuli may not require the early visual cortex, although tasks such as discrimination of orientation, color, or motion do depend on conscious perception (and early visual cortex; (Railo & Hurme, 2021)). Does the same apply to tactile modality, and if so, why?

We have also argued that the evidence presented by Ro and Koenig (2021) fails to support either their two central claims: that tactile discrimination was unconscious, and that it was based on pathways that bypass the primary somatosensory cortex. Problematically, Ro and Koenig (2021) fail to even mention the possible shortcomings of their method, or the theoretical debates surrounding the interpretation of their results. Research on unconscious processing is a good example of a psychological phenomenon that is

difficult to measure and manipulate, and debates easily boil down to methodological choices, and how observed findings are interpreted in light of existing theories. To ensure progress, studies should aim for methodological rigor and transparent interpretation of findings. Otherwise, risk is that research is divided into camps, and studies become self-fulfilling prophecies, rather than critical tests of different theories. Researchers studying the neural underpinnings of (possibly) unconscious perception need to be aware of potential biases in their methodological decisions and interpretation of results.

CRediT authorship contribution statement

Mikko Hurme: Conceptualization, Writing – original draft. **Henry Railo:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

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

References

- Ajina, S., Jünemann, K., Sahraie, A., & Bridge, H. (2021). Increased Visual Sensitivity and Occipital Activity in Patients With Hemianopia Following Vision Rehabilitation. *Journal of Neuroscience*, *41*(28), 5994–6005. <https://doi.org/10.1523/JNEUROSCI.2790-20.2021>
- Allen, C., Viola, T., Irvine, E., Sedgmond, J., Castle, H., Gray, R., & Chambers, C. D. (2020). Causal manipulation of feed-forward and recurrent processing differentially affects measures of consciousness. *Neuroscience of Consciousness*. <https://doi.org/10.1093/nc/naa015>
- Amassian, V. E., Cracco, R. Q., Maccabee, P. J., Cracco, J. B., Rudell, A., & Eberle, L. (1989). Suppression of visual perception by magnetic coil stimulation of human occipital cortex. *Electroencephalography and Clinical Neurophysiology/ Evoked Potentials*, *74*(6), 458–462. [https://doi.org/10.1016/0168-5597\(89\)90036-1](https://doi.org/10.1016/0168-5597(89)90036-1)
- Andre-Obadia, N., Garcia-Larrea, L., Garassus, P., & Mauguiere, F. (1999). Timing and characteristics of perceptual attenuation by transcranial stimulation: A study using magnetic cortical stimulation and somatosensory-evoked potentials. *Psychophysiology*, *36*(4), 476–483. <https://doi.org/10.1017/S0048577299971676>
- Campion, J., Latto, R., & Smith, Y. M. (1983). Is blindsight an effect of scattered light, spared cortex, and near-threshold vision? *Behavioral and Brain Sciences*. <https://doi.org/10.1017/S0140525X00016861>
- Center, E. G., Knight, R., Fabiani, M., Gratton, G., & Beck, D. M. (2019). Examining the role of feedback in TMS-induced visual suppression: A cautionary tale. *Consciousness and Cognition*. <https://doi.org/10.1016/j.concog.2019.102805>
- Christensen, M. S., Kristiansen, L., Rowe, J. B., & Nielsen, J. B. (2008). Action-blindsight in healthy subjects after transcranial magnetic stimulation. *Proceedings of the National Academy of Sciences*, *105*(4), 1353–1357. <https://doi.org/10.1073/pnas.0705858105>
- Cohen, L. G., Bandinelli, S., Sato, S., Kufta, C., & Hallett, M. (1991). Attenuation in detection of somatosensory stimuli by transcranial magnetic stimulation. *Electroencephalography and Clinical Neurophysiology/ Evoked Potentials Section*, *81*(5), 366–376. [https://doi.org/10.1016/0168-5597\(91\)90026-T](https://doi.org/10.1016/0168-5597(91)90026-T)
- Cowey, A. (2010). The blindsight saga. *Experimental Brain Research*. <https://doi.org/10.1007/s00221-009-1914-2>
- Ffytche, D. H., & Zeki, S. (2011). The primary visual cortex, and feedback to it, are not necessary for conscious vision. *Brain*, *134*(1), 247. <https://doi.org/10.1093/BRAIN/AWQ305>
- Garde, M. M., & Cowey, A. (2000). “Deaf hearing”: Unacknowledged detection of auditory stimuli in a patient with cerebral deafness. *Cortex*, *36*(1), 71–79. [https://doi.org/10.1016/S0010-9452\(08\)70837-2](https://doi.org/10.1016/S0010-9452(08)70837-2)
- Holmes, N. P., Tamè, L., Beeching, P., Medford, M., Rakova, M., Stuart, A., & Zeni, S. (2019). Locating primary somatosensory cortex in human brain stimulation studies: Experimental evidence. *Journal of Neurophysiology*. <https://doi.org/10.1152/JN.00641.2018>
- Hurme, M., Koivisto, M., Revonsuo, A., & Railo, H. (2017). Early processing in primary visual cortex is necessary for conscious and unconscious vision while late processing is necessary only for conscious vision in neurologically healthy humans. *NeuroImage*, *150*, 230–238. <https://doi.org/10.1016/j.neuroimage.2017.02.060>
- Ko, Y., & Lau, H. (2012). A detection theoretic explanation of blindsight suggests a link between conscious perception and metacognition. *Philosophical Transactions of the Royal Society B: Biological Sciences*. <https://doi.org/10.1098/rstb.2011.0380>
- Koivisto, M., Leino, K., Pekkarinen, A., Karttunen, J., Railo, H., & Hurme, M. (2021). TMS-induced blindsight of orientation is degraded conscious vision. *Neuroscience*. <https://doi.org/10.1016/j.NEUROSCI.2021.08.025>
- Lloyd, D. A., Abrahamyan, A., & Harris, J. A. (2013). Brain-stimulation induced blindsight: Unconscious vision or response bias? *PLoS ONE*, *8*(12), Article e82828. <https://doi.org/10.1371/journal.pone.0082828>
- Mazzi, C., Bagattini, C., & Savazzi, S. (2016). Blind-sight vs. degraded-sight: Different measures tell a different story. *Frontiers in Psychology*, *7*(JUN), 901. <https://doi.org/10.3389/fpsyg.2016.00901>
- Michel, M., & Lau, H. (2021). Is blindsight possible under signal detection theory? Comment on Phillips (2021). *Psychological Review*, *128*(3), 585–591. <https://doi.org/10.1037/REV0000266>
- Overgaard, M., Feh, K., Mouridsen, K., Bergholt, B., & Cleeremans, A. (2008). Seeing without seeing? Degraded conscious vision in a blindsight patient. *PLoS ONE*, *3*(8), Article e3028. <https://doi.org/10.1371/journal.pone.0003028>
- Paillard, J., Michel, F., & Stelmach, G. (1983). Localization Without Content: A Tactile Analogue of ‘Blind Sight’. *Archives of Neurology*. <https://doi.org/10.1001/archneur.1983.04050080048008>
- Peters, M. A. K., & Lau, H. (2015). Human observers have optimal introspective access to perceptual processes even for visually masked stimuli. *eLife*. <https://doi.org/10.7554/eLife.09651>
- Phillips, I. (2020). Blindsight Is Qualitatively Degraded Conscious Vision. *Psychological Review*. <https://doi.org/10.1037/rev0000254>
- Phillips, I. (2021). Bias and blindsight: A reply to Michel and Lau (2021). *Psychological Review*, *128*(3), 592–595. <https://doi.org/10.1037/REV0000277>
- Pöppel, E., Held, R., & Frost, D. (1973). Residual visual function after Brain Wounds involving the central visual pathways in Man. *Nature*, *243*(5405), 295–296. <https://doi.org/10.1038/243295a0>
- Railo, H., & Koivisto, M. (2012). Two means of suppressing visual awareness: A direct comparison of visual masking and transcranial magnetic stimulation. *Cortex*, *48*(3), 333–343. <https://doi.org/10.1016/j.cortex.2010.12.001>
- Railo, H., Piccin, R., & Lukasik, K. M. (2021). Subliminal perception is continuous with conscious vision and can be predicted from prestimulus electroencephalographic activity. *European Journal of Neuroscience*. <https://doi.org/10.1111/EJN.15354>
- Railo, H., & Hurme, M. (2021). Is the primary visual cortex necessary for blindsight-like behavior? Review of transcranial magnetic stimulation studies in neurologically healthy individuals. *Neuroscience & Biobehavioral Reviews*, *127*, 353–364. <https://doi.org/10.1016/j.neubiorev.2021.04.038>
- Ramsøy, T. Z., & Overgaard, M. (2004). Introspection and subliminal perception. *Phenomenology and the Cognitive Sciences*. <https://doi.org/10.1023/b:phen.0000041900.30172.e8>
- Ro, T., & Koenig, L. (2021). Unconscious Touch Perception After Disruption of the Primary Somatosensory Cortex. *Psychological Science*. <https://doi.org/10.1177/0956797620970551>

- Rossetti, Y., Rode, G., Rode, G., & Boisson, D. (1995). Implicit processing of somesthetic information: A dissociation between where and how? *NeuroReport*, 6(3), 506–510. <https://doi.org/10.1097/00001756-199502000-00025>
- Saionz, E. L., Tadin, D., Melnick, M. D., & Huxlin, K. R. (2020). Functional preservation and enhanced capacity for visual restoration in subacute occipital stroke. *Brain: A Journal of Neurology*, 143(6), 1857–1872. <https://doi.org/10.1093/BRAIN/AWAA128>
- Salminen-Vaparanta, N., Koivisto, M., Noreika, V., Vanni, S., & Revonsuo, A. (2012). Neuronavigated transcranial magnetic stimulation suggests that area V2 is necessary for visual awareness. *Neuropsychologia*, 50(7), 1621–1627. <https://doi.org/10.1016/j.neuropsychologia.2012.03.015>
- Salminen-Vaparanta, N., Koivisto, M., Vorobyev, V., Alakurtti, K., & Revonsuo, A. (2019). Does TMS on V3 block conscious visual perception? *Neuropsychologia*, 128, 223–231. <https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2017.11.013>
- Seyal, M., Masuoka, L. K., & Browne, J. K. (1992). Suppression of cutaneous perception by magnetic pulse stimulation of the human brain. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, 85(6), 397–401. [https://doi.org/10.1016/0168-5597\(92\)90053-E](https://doi.org/10.1016/0168-5597(92)90053-E)
- Thielscher, A., Reichenbach, A., Uurbil, K., & Uluda, K. (2010). The cortical site of visual suppression by transcranial magnetic stimulation. *Cerebral Cortex (New York, N.Y. : 1991)*, 20(2), 328–338. <https://doi.org/10.1093/CERCOR/BHP102>
- Weiskrantz, L., Warrington, E. K., Sanders, M. D., & Marshall, J. (1974). Visual capacity in the hemianopic field following a restricted occipital ablation. *Brain*, 97(4), 709–728. <https://doi.org/10.1093/brain/97.4.709>
- Witt, J. K., Taylor, J. E. T., Sugovic, M., & Wixted, J. T. (2015). Signal detection measures cannot distinguish perceptual biases from response biases. *Perception*. <https://doi.org/10.1068/p7908>