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Reply to 'Efficiency and capacity mechanisms may coexist during training-induced cognitive changes'

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In our Review (von Bastian, C., Belleville, S., Udale, R., Reinhartz, A., Essounni, M. & Strobach, T., Mechanisms underlying training-induced cognitive change, *Nat Rev Psychol* **1**, 30-41, (2022)[1]), we discussed the capacity-efficiency framework of cognitive training and transfer to explain effects of cognitive training. We are excited that other authors are starting to use our framework to systematize and interpret findings in this field. In our article, we focused on human behavioural and brain imaging studies but appreciate that evidence from all sources, including animal and genetic studies, should be considered to build a comprehensive science of cognitive change. We thank Zhang and Sauce for bringing evidence from these domains to our attention (Zhang, D.-W. & Sauce, B., Efficiency and capacity change can coexist in cognitive training, *Nat Rev Psychol* http://dx.doi.org/xxx (2022)[2]).

Zhang and Sauce emphasize that changes in capacity and efficiency are not necessarily mutually exclusive but can coexist. Indeed, this statement is in line with our assumptions and was stated in the original article. Specifically, Zhang and Sauce claim that some training-related changes, specifically in working memory, can be attributed to the capacity mechanism. However, the current brain imaging literature does not provide convincing evidence for such changes in capacity. Existing working memory training studies reporting brain imaging data have shown both increases and decreases of brain activation after working memory training[3]. Still, meta-analytic evidence suggests that these changes in activation patterns likely reflect mere redistributions of these activation patterns within the same core working memory networks rather than a recruitment of additional resources[4]. Critically, increases and decreases of blood-oxygen level dependent (BOLD) signal do not map directly onto specific underlying neurobiological mechanisms. Research is still needed to lay the groundwork to identify how changes in brain activation patterns relate to changes in cognitive capacity and efficiency[3].

Furthermore, determining how training – or the other factors Zhang and Sauce[2] mentioned that may affect capacity, such as schooling, poverty, and maturation – impact neural correlates of cognitive capacity and efficiency will require moving beyond just assessing overall behavioural performance. For example, Zhang and Sauce[2] make the point that increases in frontoparietal activation correlate with improvements in working memory. However, working memory training studies to date almost exclusively report overall working memory performance. Changes in overall performance can reflect changes in working memory capacity, efficiency, or both. For example, overall performance can be boosted by increased efficiency, for example through changes in strategic approach or increased familiarity-based processing[5]. Computational modelling approaches can help disentangle components of working memory performance (for example, the quantity and quality of representations activated in working memory[6]). By using such computational approaches to formalise training-induced changes in working memory capacity and efficiency, the derived parameter estimates can then be correlated with changes in BOLD signal. This method could, therefore, determine whether changes in activation patterns reflect changes in capacity, efficiency, or both.

We agree with Zhang and Sauce[2] that changes in dopamine D1 receptor density and sensitivity in response to cognitive demands[7] and training[8] in mice is intriguing and speaks to a remarkable flexibility of the cognitive system. These findings also highlight the relevance of animal and genetic studies for the human cognitive training literature. However, similarly to the observed changes in BOLD signal, without a more fine-grained understanding of the behavioural correlates of these changes, at present it is difficult to conclusively interpret to what extent this responsiveness reflects changes in overall capacity or flexible adjustments in resource allocation to accommodate fluid changes in environmental demands.

In summary, the evidence discussed by Zhang and Sauce is relevant to considering capacity and efficiency mechanisms but does not provide unequivocal evidence of capacity change.

Competing interests: The authors declare no competing interests.

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