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Abdullah Almaatouq, Thomas L. Griffiths, Jordan W. Suchow, Mark E. Whiting, James Evans, and Duncan J. Watts

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Title of commentary
Neuroadaptive Bayesian Optimisation can allow integrative design spaces at the individual level in the Social and Behavioural Sciences… and beyond

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Abstract

Almaatouq and colleagues (2022) propose an integrative experimental design space combined with large samples for scientific advancement. We argue recent innovative designs combining closed-loop experimental designs and Bayesian Optimisation allow for integrative experiments at an individual level during a single session, circumventing the necessity for large samples. This method can be applied across disciplines, including developmental and clinical research.

Main text

Almaatouq et al. (2022) propose that to improve the generalisability and efficiency of the research in the social and behavioral sciences, experiments should be systematically selected from a large design space. The authors argue that this approach requires the application of the paradigm to large samples and thus extensive collaboration. However, we believe that large samples are useful but not necessary to systematically probe the topography of experimental space. Recently, a conceptually comparable approach called Neuroadaptive Bayesian Optimisation has been developed in neuroimaging (NBO). NBO does not require large samples and can operate on an individual level in real-time. We propose this approach can also be generalised to the social and cognitive sciences to further the design proposed by Almaatouq and colleagues.

NBO combines real-time analysis of participants' responses and machine learning into a closed-loop design to find the experimental parameters that maximise the target (cognitive or brain) measure while sampling across a large design space (Lorenz et al., 2017) (Figure 1). Bayesian Optimisation (BO) is an active sampling technique that learns from input data collected during a single experimental testing session. The algorithm uses an acquisition function that balances exploration and exploitation to select an experiment (e.g., a particular combination of characteristics of the presented stimulus) for presentation to the participant from the experimental design space (Brochu et al., 2010). Target measures are collected and modelled across the design space using Gaussian process regression. Through an iterative process of sampling the search space, a surrogate model of the target response across the full design space is estimated and updated with every sampling. BO will select the next experiment in the design space in an explorative manner early during the session (areas that have not been sampled yet and for which the uncertainty regarding the relationship with the target measure is high) and an exploitative manner towards the end of the session (areas that show the maximum brain/cognitive response and have been sampled previously such that predictability of the response is high). The NBO converges on the area of the design space that maximises the target measure for that individual participant within a few iterations, if the target measure is reliable and the effect size is sufficient. In one early study, researchers constructed an experimental space based on a meta-analysis of existing literature (as suggested by Almaatouq and colleagues), and used NBO with real-time fMRI analysis to identify cognitive tasks that maximally dissociated between frontoparietal attention networks at the individual level (Lorenz et al., 2018). Thus, NBO brings an integrative experimental design approach to the level of the individual through incorporating the tools of active learning with real-time data analysis.

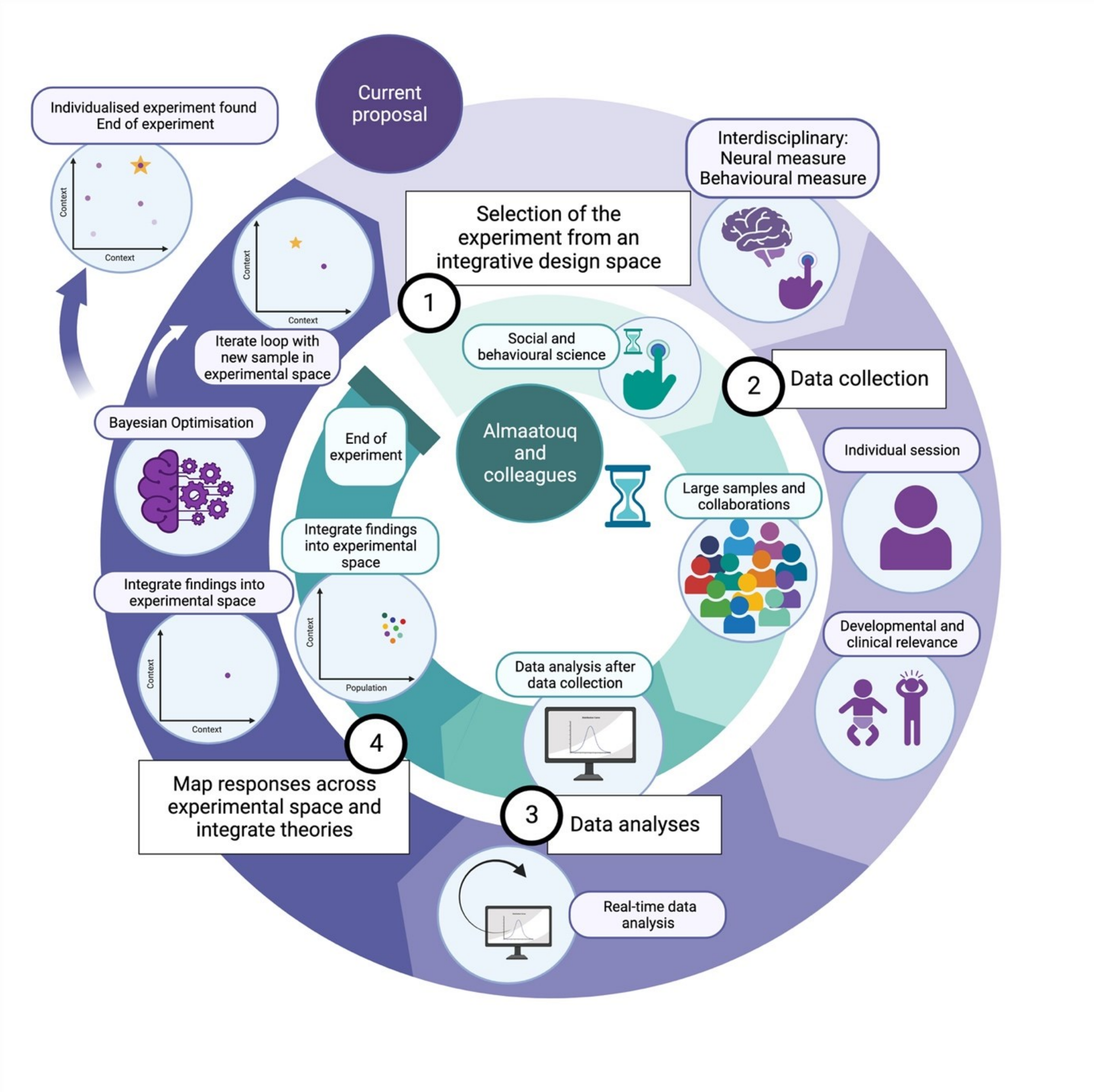

Figure 1. Overview of the integrative experimental design proposed by Almaatouq and colleagues (inner circle) and how it is operationalised in the Neuroadaptive Optimisation (NBO) approach described in the current proposal (outer circle). This figure was created with Biorender.com.

We argue that integrative experimental designs as proposed may have parallels across multiple fields, and interdisciplinary exchange may be fruitful. NBO is currently being applied in developmental science to examine social development in infants (Gui et al., 2022; Wass & Jones, 2023). Developmental researchers typically preselect a limited range of experimental conditions or stimuli based on specific theories. Similar to issues in social science identified by Almaatouq and colleagues, this has limited progress because each study only probes selected questions and the relationship between theoretical models or different experimental designs remains uncharacterised. In contrast, integrative experimental designs allow experimenters to map brain or behavioural responses across a larger experimental space, including providing out-of-sample predictions for stimuli that are unsampled. This enables developmental researchers to simultaneously test multiple developmental theories through considering their predictions for the variation in responses across a larger space, in accordance with Almaatouq and colleagues' proposal. This approach can be extended to other multi-dimensional spaces with different concepts mapped across dimensions of the search space, for example to explore the influence of contingency or sensitivity on infant attention.

Beyond testing theories in basic science, we think integrative experimental designs may also have clinical utility (Lorenz et al., 2017, 2021). We currently lack objective biomarkers with clinical utility for psychiatric conditions (Loth, 2023). As in the social sciences described by Almaatouq and colleagues, the field of psychiatry is challenged by reproducibility issues that stem from heterogeneity in participant populations, selection of single tasks based on particular theories, and broad analytic flexibility of the resulting data. This leads to difficulty with integrating clinical findings from different studies and hinders biomarker discovery. Integrative experimental designs allow researchers to expand the search space across multiple different tasks or analysis pipelines (Lorenz et al., 2017). Adaptive designs can then be used to select the task and/or pipeline that shows greater individual deviation from population norms for a particular person, similar to Almaatouq and colleagues' proposal of mapping individual-level traits across a design space. For example, NBO has recently been used to identify tasks sensitive to residual network function in individual patients with stroke and higher dissimilarity in responses in patients compared to controls (Lorenz et al., 2021). Similarly, an experimental space can be constructed through characterising the similarity space of the output of different neuroimaging analysis pipelines and identify a pipeline with the most experimental sensitive contrasts, illustrating one way in which the 'cartographer' can assign numerical coordinates to different locations in space (Dafflon et al., 2022).

In summary, we argue that the approach proposed by Almaatouq and colleagues has relevance beyond the boundaries of social and behavioral sciences, and can be extended to the individual level by deploying active learning using real-time feedback during the data collection session itself (Figure 1). Current implementations in developmental and clinical samples indicate that NBO is particularly promising in samples characterised by high heterogeneity. Further, the NBO approach can be generalised to the social sciences through use of real-time behavioural data collection (i.e., decisions, reaction times or opinions). Integrative experimental approaches applied at the individual level using real-time data collection, such as NBO, will allow us to conduct reliable research that does not depend on large sample sizes and that can be applied in screening and clinical programs, answering to Almaatouq et al.'s call to produce unbiased scientific findings that apply to particular real-world contexts.

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Competing Interest Statement
The authors declare none.

Alphabetical reference list

Almaatouq, A., Griffiths, T. L., Suchow, J. W., Whiting, M. E., Evans, J., & Watts, D. J. (2022). Beyond Playing 20 Questions with Nature: Integrative Experiment Design in the Social and Behavioral Sciences. *Behavioral and Brain Sciences*, 1–55. https://doi.org/10.1017/S0140525X22002874

Brochu, E., Cora, V. M., & de Freitas, N. (2010). *A Tutorial on Bayesian Optimization of Expensive Cost Functions, with Application to Active User Modeling and Hierarchical Reinforcement Learning*. https://arxiv.org/pdf/1012.2599.pdf

Dafflon, J., da Costa, P. F., Vasa, F., Monti, R. P., Bzdok, D., Hellyer, P. J., Turkheimer, F. E., Smallwood, J., Jones, E. J. H., & Leech, R. (2022). *Into the multiverse of neuroimaging analyses*.

Gui, A., Throm, E. V., da Costa, P. F., Haartsen, R., Leech, R., & Jones, E. J. H. (2022). Proving and improving the reliability of infant research with neuroadaptive Bayesian optimization. *Infant and Child Development*, *31*(5), 1–6. https://doi.org/10.1002/icd.2323

Lorenz, R., Hampshire, A., & Leech, R. (2017). Neuroadaptive Bayesian Optimization and Hypothesis Testing. *Trends in Cognitive Sciences*, *21*(3), 155–167. https://doi.org/10.1016/J.TICS.2017.01.006

Lorenz, R., Johal, M., Dick, F., Hampshire, A., Leech, R., & Geranmayeh, F. (2021). A Bayesian optimization approach for rapidly mapping residual network function in stroke. *Brain*, *144*(7), 2120–2134. https://doi.org/10.1093/brain/awab109

Lorenz, R., Violante, I. R., Monti, R. P., Montana, G., Hampshire, A., & Leech, R. (2018). Dissociating frontoparietal brain networks with neuroadaptive Bayesian optimization. *Nature Communications*, *9*(1), 1227. https://doi.org/10.1038/s41467-018-03657-3

Loth, E. (2023). Does the current state of biomarker discovery in autism reflect the limits of reductionism in precision medicine ? Suggestions for an integrative approach that considers dynamic mechanisms between brain , body , and the social environment. *Frontiers in Psychiatry*, *14*(1085445), 1–12. https://doi.org/10.3389/fpsyt.2023.1085445

Wass, S., & Jones, E. J. H. (2023). Editorial perspective: Leaving the baby in the bathwater in neurodevelopmental research. *Journal of Child Psychology and Psychiatry and Allied Disciplines*. https://doi.org/10.1111/jcpp.13750