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Expertise and generalization: lessons from action video games

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Training is typically characterized by a trade-off between developing efficient performance, or expertise, and maintaining the ability to generalize one's knowledge beyond the trained domain. Here we ask whether it may be possible to train individuals to enhance their generalization abilities despite this natural trade-off. We first review the proposal that enhanced attentional control and cognitive flexibility may be potential mechanisms that will produce broad generalization. We then consider the case of action video game play which has been associated with enhancements in both attentional control and cognitive flexibility as well as generalization beyond the trained intervention.

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Expertise: a double-edged sword

Expertise, or reaching an outstanding level of skill in one domain, is typically the result of thousands of hours of practice in the given domain. And while the path to expertise is commonly multi-faceted, it is nearly always the case that some degree of automatization of function can be found at the heart of expert level performance. Such automatization allows what were initially complex and cognitively demanding sequences of actions or thoughts to be executed automatically with minimal effort and/or cognitive load. This not only serves to produce actions or thoughts that are fast and accurate, but critically, releases limited cognitive resources for alternative tasks. For example, a novice who is first learning to drive a manual transmission car may need to expend considerable cognitive effort determining what pedal to press, which direction to move the shift knob, among others. This in turn leaves no resources free for conversing with the front seat passenger or following a map. Conversely, in an expert driver, basic driving functions have been largely automatized and cognitive resources are thus available to complete these additional tasks.

However, while there is clear value to automatizing function, it has long been accepted that automatization also comes at a cost [1,2]. In particular, by repeating the same task over and over, experts may develop skills that are so task-specific that they lack the flexibility to adapt to alterations in the automatized tasks and sub-tasks [3–7]. For example, the performance of skilled typists plummets when certain seemingly minor changes are made in the keyboard characteristics [8]. Together, the evidence strongly supports the idea that expertise is often accompanied by the development of skills that are incredibly specific to only those precise actions/thoughts associated with skilled performance. What is less clear is whether it is possible to train individuals to become experts, not at a specific task or domain, but rather at flexibly adapting and transferring their skills and knowledge as new circumstances arise?

Training that fosters generalization — lessons from action video game play

Over the past 15 years, evidence has accumulated showing that playing one particular form of video game, known as action video games (primarily what are known as first-person or third-person shooter video games), leads to rather broad generalization, with performance enhancements noted in domains as varied as visual perception (e.g., enhanced contrast sensitivity & better peripheral detection — [9–11]), top-down attention (e.g., better change detection, reduction in attentional capture [12–15]), visuo-spatial cognition (e.g., better mental rotation; enhanced visual short-term memory [16,17]) and finally multi-tasking and task switching (e.g., lesser switch cost, greater ease at multi-tasking [18–20]). In a recent meta-analysis combining the results of 73 studies and 3773 total participants, self-declared action video game players were found to outperform non-gamers by about half a standard deviation across all aspects of cognition combined. Importantly, the same trend was seen when considering only true experiments, wherein non-gamer participants were specifically trained on an action video game and any cognitive gains were contrasted against those seen in an active control group that was trained on a commercial non-action video game. Indeed, a second meta-analysis on 21 intervention studies involving 609 participants showed that action game training produced a benefit on cognition of around 1/3 of a standard deviation (as compared to control-trained individuals) [21••]. Such results indicate that action video game play is not just correlated with enhanced cognitive abilities, but does in fact, cause improvements in these abilities.

The broad generalization seen to result from action video game training is consistent with the fact that such games naturally mesh complexity, novelty, and variability, ensuring the game play can never be fully automatized [22•,23]. Action gamers certainly develop some game-specific behaviors akin to expertise after hours spent on a particular title, as when gamers anecdotally report that they cannot play a game where the *y*-axis mapping is different from their practiced routine (i.e., whether pushing the mouse up makes the player look up or look down). Yet, the incredible diversity of situations encountered across various action video game titles ensures constant engagement of two key cognitive processes: attentional control and cognitive flexibility. For instance, because enemies can appear at virtually any location, at any time, in any number/combinations, it is not possible to learn an automatic sequence of actions that will produce game success. Instead, action video games continuously challenge attention allocation and the flexible evaluation of goals and sub-goals [24••,25]. A key prediction of this work is that playing such games results in enhanced attentional control and cognitive flexibility which in turn fosters generalization.

Attentional control and cognitive flexibility are two central and complementary executive functions [26,27], which, as predicted, are enhanced after action video game play. Many behavioral studies now document enhancements associated with action video game play on a range of tasks tapping attentional control — from an enhanced ability to redirect eye-gaze and attention when initially wrongly allocated [15,28], to superior visual search performance [14,29], to better distractor suppression [30]. Similarly, although less well established, action video game play has also been positively associated with tasks requiring cognitive flexibility such as multi-tasking, task switching, or forms of working memory [16,20]. An efficient diagnostic task to assess the two key components of attentional control and cognitive flexibility appears to be the Multiple Object Tracking task, wherein individuals must track moving objects from amongst a display containing many visually identical distractor objects. This task requires both attentional tracking over time and flexible working memory indexing and updating. Accordingly, this task has recently been shown to load on two orthogonal factors: one related to a generalized capacity for efficient perception and awareness — a key function of attentional control — the other related to cognitive flexibility — or the capacity to hold and flexibly manipulate information in working memory [31].

A prediction: an inverted U-shape curve for generalization as training proceeds

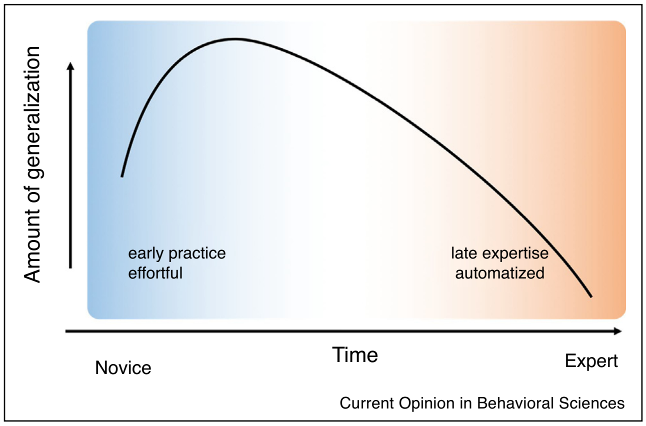
Enhanced attentional control and cognitive flexibility have been proposed to provide a mechanism for generalization, while expertise is achieved at least partially via automatization, a process that inherently entails releasing demands on attentional control and cognitive flexibility. As expertise sets in, these two functions become less challenged and their enhancement is expected to fade away. Indeed, much as physical fitness decays in the absence of continued physical demand, so do enhancements in cognitive abilities in the absence of continued cognitive demand [32,33]. Generalization is therefore expected to decrease as learning progresses toward expertise, a prediction in line with the highly specific skilled performance noted in experts.

Generalization is also expected to be rather limited during the earliest stages of training. This early period is characterized by a quickly saturating learning phase that mostly corresponds to the learners' mastering the basic rules or strategies required by the new task. Learning these basic rules is certainly demanding, tapping long-term memory systems in particular. Yet, until these rules are somewhat consolidated, it will be unclear to the learner to what, or how to direct their processing resources, thus minimizing the overall load on both attentional control and cognitive flexibility. To clarify this point, consider an athlete playing a new sport. Until the fundamental rules, goals, and strategies of the sport are understood, the physical challenge will not be maximal. The same idea applies here with respect to cognitive challenges.

The phase of learning predicted to induce the greatest generalization is therefore after this earliest phase, but before expertise sets in. It corresponds to a phase of learning which is rather slow and often associated with the view that 'practice makes perfect.' Early in the slow learning phase, the task is sufficiently well understood to result in load being placed on attentional control and cognitive flexibility — load which will, of course, be slowly released as the learning moves toward expertise. Thus, generalization as a function of training time is expected to be an asymmetric U-shaped curve (Figure 1).

Although this remains a prediction, it is instructive to consider such a view in the context of the impact of playing the video game Tetris on mental rotation. Given the above framework, we would expect naïve participants who are asked to play an intermediate amount of Tetris (e.g., 10–30 hours), to show some degree of transfer from their Tetris training to new mental rotation tasks. Such a finding has indeed been documented in the existing literature [34,35]. At the same time, we would also expect that expert Tetris players — i.e., individuals who play competitively and who have hundreds, if not thousands,

Figure 1



Proposed conceptualization of the relationship between learning phases and amount of generalization. In the very earliest phase of training, the expected amount of generalization is low for the simple reason that not much has yet been learned that could generalize. As participants move through the early-to-intermediate phase of training, the task is expected to be demanding in terms of processing resources resulting in enhancements in attentional control and cognitive flexibility, and as a result, greater generalization is expected. Finally, at some point, task functions begin to be automatized. Although the task itself is performed with increasing efficiency, the learning that subserves such changes in performance is tightly tied to the specific of the task releasing the pressure on attentional control and cognitive flexibility and thus lesser degrees of generalization are expected.

of hours of Tetris experience — should not show stunning enhancements in mental rotation ability. Instead, they would be expected to mainly excel only at the rotation of Tetris-like shapes, as would be facilitated by automatizing the action sequences that link each of the various board configurations to the 7 possible Tetris shapes. Although such automatization would release cognitive load and greatly facilitate performance, it would obviously be of little value for any mental rotation task that does not employ Tetris shapes as documented by previous work [36,37]. Although there has not yet been a systematic investigation of mental rotation generalization as a function of the number of hours of Tetris play, the available data is in line with this view of the time course of generalization. More titrated studies though would provide a valuable test of the trade-off between generalization and automatization as training proceeds.

We note that a major challenge in understanding the trade-off between generalization and expertise is that the time course of learning, and thus the time needed to reach expertise, varies widely across domains. Expertise in playing simple brain games develops quite fast; accordingly learning to play simple brain games has been associated with limited generalization [38]. By contrast, expertise when learning to play musical instruments or other long-term activities such as chess develops slowly and accordingly the learning of these complex activities has been associated with greater generalization [39,40••]. In line with the key prediction from the proposed view training paradigms that are likely to produce the most generalization are the ones that keep a high load on attentional control and cognitive flexibility.

The mechanisms by which attentional control and cognitive flexibility may favor generalization

To understand how attentional control and cognitive flexibility may foster generalization, it helps to differentiate between two different ways that generalization can be assessed. The first, and most common, approach to assessing generalization involves training an individual on a given task, and then examining the extent to which the training produces immediate benefits on new, untrained tasks. This approach goes back to Thorndike's '*common elements*' hypothesis, where the prediction is that immediately better performance on the generalization task will only be observed to the extent that the training and generalization tasks share key processing components [41–43]. A less commonly employed approach to examining generalization involves examining the extent to which training facilitates the learning of new tasks (i.e., by contrast to only examining initial performance on the new tasks — [24••]). This approach recognizes that it is possible for previous training to facilitate the acquisition of the new task (whether or not immediate benefits are also observed on the new task). This latter form of generalization has been referred to as 'learning to learn'. Of course, these two forms of generalization are not mutually exclusive and could co-occur.

Critically, enhanced attentional control/cognitive flexibility offers a natural mechanism for the learning to learn form of generalization. Enhanced attentional control allows for better extraction of task-relevant information once the individual understands the basic rules/goals of the task. This in turn not only allows for more informed decisions to be made on each trial of the task, it will also facilitate learning as more information about the task is extracted on each trial [44,45]. And because the ratio of signal-to-noise affects performance in many distinct tasks, this would serve to account for the rather broad generalization produced by training known to enhance attentional control and cognitive flexibility — such as action video game play [46]. Greater cognitive flexibility also allows one to more gracefully adapt to new tasks, to update memory information and to re-evaluate goals and subgoals as they change, all of which are similarly likely to facilitate learning or asymptotic performance in many tasks and domains.

Enhanced attentional control and cognitive flexibility therefore offers a complementary mechanism to the prevalent view of generalization, which focuses primarily on the extent to which the training and generalization tasks share processing components. Importantly, while the former mechanism (learning to learn) allows for forms of relatively 'far' generalization, the latter exclusively predicts 'near' generalization (as, by definition, only 'near' tasks will share the most processing components). Note that a fundamental issue remains in characterizing generalization as far versus near in that we currently lack a theoretical framework to systematically identify the relevant level of overlap between any two tasks for predicting generalization [47,48]. Clearly, this is a computational challenge that awaits to be addressed in future research.

Conclusion

We have considered how the delicate balance between the demands of learning and the development of automatization as expertise sets in may affect generalization. We propose that generalization will be broadest during early-to-intermediate phases of learning, where the basic task rules and structures are known, but high demands on attentional control and cognitive flexibility remain. The case of action video games is interesting because it represents a case of persistent extreme load on attentional control and cognitive flexibility, forcing individuals to make decisions in an ever-changing environment at a pace that is difficult to match in other activities. We propose here that the incredible diversity of situations encountered across various video game titles ensures constant engagement of attentional control and cognitive flexibility, fostering in turn greater adaptability and generalization when facing new tasks or domains.

Conflict of interest statement

Bavelier is on the scientific advisory board of Akili Interactive, Boston

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