Use of Complementary Actions Decreases with Expertise

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Abstract

Based on data collected during play of the fast-paced video game of Tetris, it has long been claimed that *complementary* (or epistemic) *actions* increase with expertise (Kirsh, 1995; Kirsh & Maglio, 1994; Maglio & Kirsh, 1996). *Complementary* actions use the environment to provide information that would otherwise require mental processing. They stand in contrast to *pragmatic* actions, which operate to bring the current state closer to the goal state. Although complementary actions undoubtedly exist, we question the conclusion that they increase with expertise. First, classifying actions made in a fast-paced video game can be very difficult. Second, the range of expertise considered in prior studies has been very small. We sample a wide range of Tetris expertise and define complementary actions across multiple criterion of varying strictness. Contrary to prior work, our data suggest that complementary actions decrease with expertise, regardless of the criterion used.

Keywords: epistemic action, complementary action, pragmatic action, expertise, games, Tetris, soft constraints hypothesis, embodied cognition

Substituting Actions in-the-world for Processes in-the-head

Complementary actions (originally called *epistemic actions* in Kirsh & Maglio, 1994; renamed in Kirsh, 1995) are external acts that provide information about a task environment faster than could be achieved by internal mental processes. Such actions stand in contrast to *pragmatic actions*, which are external actions that bring the current state closer to the goal state. The classic example of a complementary action in Tetris is physically versus mentally rotating a piece to determine which orientation produces the best fit to the board below. *Hence, complementary actions substitute actions in-the-world for processes in-the-head.*

Complementary actions are a powerful argument for embodied cognition (Clark, 2008), contrasting greatly with the notion that people perform all computation in the head. Although complementary actions undoubtedly exist, we question the claim that they increase in prevalence with expertise (Kirsh & Maglio, 1994). As mental processing times generally transition from slower controlled to faster automatic processing with experience (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977) we would have expected the incidence of complementary actions to decrease with experience as internal processes became more competitive with external actions.

The suggestion that complementary actions increase under circumstances (i.e., increases in practice) in which the time cost of mental operations can be presumed to be decreasing appears to suggest a preference for embodied actions that runs contrary to what has been found in other circumstances. In those studies we (Gray & Fu, 2004; Gray, Sims, Fu, & Schoelles, 2006) and others (Bourne, Raymond, & Healy, 2010; Morgan, Patrick, Waldron, King, & Patrick, 2009; Morgan, Waldron, King, & Patrick, 2007; Waldron, Patrick, Duggan, Banbury, & Howes, 2008; Waldron, Patrick, Morgan, & King, 2007) have found a more neutral cost-accounting which has led us to maintain that systems for cognitive control make, "no functional distinction between knowledge in-the-head versus in-the-world or the means of acquiring that information (such as eye movement, mouse movement and click, or retrieval from memory)" (Gray & Veksler, 2005).

Complementary Actions and Expertise

Obviously the claim that complementary actions increase with expertise requires strong criterion for identifying complementary actions when they occur and also requires sampling across a wide range of expertise.

As we have no access to an individual's intentions, observations of behavior may yield ambiguous data. We must instead algorithmically define and computationally extract behaviors from log files made during performance so that our classification of behavior is free from observer bias. In this paper we will discuss five criteria that we selected for classifying complementary actions in the video game *Tetris*, and the implications of each. Data for all classifying algorithms are presented.

To determine whether complementary actions increase with expertise we need to ensure that we sample across a wide range of player expertise. We find the level of expertise of the players in Kirsh and Maglio's reports to be extremely limited. In contrast, we present data from 59 players whose Tetris performance spans the range from what would be expected of beginners (but not novices) to extreme expertise. To preview our conclusions, except by our most lenient criteria, we find nearly no evidence of complementary actions. Our two most lenient criteria suggest that complementary actions increase with skill early on but then decrease as skill rises to expert levels. All of our criteria suggest that complementary actions do not play a role in expertise. Intriguingly, our most lenient criteria suggest that complementary actions have a role in acquiring expertise.

Why Tetris?

Tetris is a responsive and fast-paced game that requires high concentration. These features make it an excellent environment to study time-stressed decision-making. As people generally enjoy playing it, Tetris experts are easy to find.

Kirsh and Maglio describe two complementary uses for the two main actions in Tetris: *translating* the shape (moving it towards the left or right) and *rotating* it. In regards to translation, in order to save the mental effort of perceptually verifying that the current piece (called a Tetrazoid, which we will henceforth refer to as a zoid) is lined up with the target area within the accumulation at the bottom of the display, the player may translate the shape all the way to the wall nearest the target area and then count keypresses to determine, for example, that the zoid is above the 3rd rather than the 2nd column from the left.

Rotating the shape is a more complex scenario. Kirsh and Maglio describe the following five uses:

1. Unearthing new information very early in the episode[1]
2. Saving mental rotation effort
3. Facilitating retrieval of zoids from memory
4. Making it easier to identify a zoid's type
5. Simplifying the process of matching zoid and contour

The first item in this list, the action of early rotation, refers to the moment the zoid first appears on the screen. In the version of Tetris used by Kirsh and Maglio, only the bottommost segment of the piece is initially visible, the rest of the zoid remaining hidden above the field of view. At this stage the piece is likely to be ambiguous, as only one or two of the four segments of the zoid are visible. When players rotate the piece at this stage, Kirsh and Maglio (1994) argue that it is a complementary action (p. 527), as it serves the epistemic function of uncovering more information about the piece and is not directly involved in placing the piece in its final position. However, this action does not fall in line with the definition of complementary actions put forth earlier in the same paper (p. 514):

> [W]e use the term epistemic [or complementary] action to designate a physical action whose primary function is to improve cognition by:
> 1. Reducing the memory involved in mental computation, that is, space complexity;
> 2. Reducing the number of steps involved in mental computation, that is, time complexity;
> 3. Reducing the probability of error of mental computation, that is, unreliability.

The act of early rotation of a zoid uncovers information that was previously unavailable to the player. Prior to performing this action, it would have been impossible for the player to properly plan where the current zoid should finally be placed. So, while the act of early rotation would be considered exploration of the environment (Kirsh, 1996) in the context of the game, this information is prerequisite to the overall pragmatic action plan of the episode. It does not merely reduce space complexity, time complexity, or unreliability of mental computation; it *enables* mental computation at this early stage. If a player were to wait for the zoid to be completely displayed before beginning to formulate a pragmatic plan, up to 600 milliseconds of planning and action time would be lost (depending on the current level of play). A good pragmatic action plan, then, would include the discovery of the zoid type as quickly as possible as a step toward efficiently placing the piece in its final position. *Thus, although this type of action provides information gains for the player, it cannot be replaced by a mental process and is primarily pragmatic in function.*

In the version of *Tetris* we use there is no phase in which early rotations can occur as the pieces initially appear along the topmost edge of the screen in their entirety. Because these "early rotations" do not fit the definition of complementary actions, omission of this phase allows us to more easily extract those actions that should be classified as complementary as well as stay in line with the rules of the game of *Tetris* in its original form.

Complementary actions are difficult to classify

It is not the case that every single action taken in a *Tetris* episode is either pragmatic or complementary; there are many situations in which a player will input a command into the game that neither moves the zoid closer to where it eventually ends up, nor makes cognition easier by substituting physical effort for mental effort. Certainly even expert players make errors, but even errors do not account for all the possible actions a player may take.

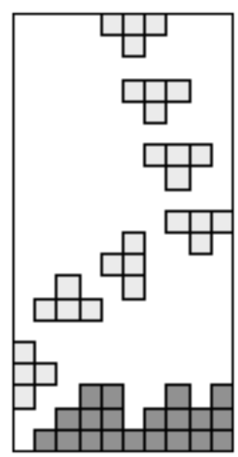

Figure 1: Goal switching

What is the most sensible way to classify the actions taken in Figure 1? The light gray pieces represent the progression of one piece's position from the top of the display through time, during the course of one episode. Here, a T-shaped zoid appears at the top of the display, is translated right three spaces, then is translated all the way to the left side of the screen while being rotated three times. The first three actions of this placement routine cannot be pragmatic, for they move the zoid *away* from its final position on the board. Surely, however, these actions also cannot be complementary, for there is no extra knowledge gained from the routine – moving the shape all the way to the right does not make moving the shape all the way to the left any easier, and does not help in determining where the

[1] Where an *episode* is defined as the time from the appearance to the placement of a zoid.

best place to position the piece would be. Since the three actions in question are consecutive, it is unlikely, although possible, that the actions are due to error.

What is more likely is that the player simply decided to place the zoid in a different location. Instead of performing a full analysis of the state of the gameworld when the zoid appears, perhaps the player chose the first solution that passes an individual threshold of fitness.

One metric for assessing the fitness of a zoid is to count the number of edges that will fit flush with the other zoids in the accumulation when placed (Kirsh & Maglio, 1994). In the case of this example, the player translates the shape into a sensible position, matching five contours on the shape to the accumulation, but then sees a better option – by translating the zoid all the way to the left and rotating it three times, the end result is that only four contours are matched, but two lines are cleared[2], which results in lowering the accumulation of pieces by two rows and a score increase of 100 points.

This type of scenario is common in Tetris; players will often see a better position for their zoid after they have made a decision about where to place it and have already begun to carry out a motor plan to rotate and translate it into the proper position. They must then decide whether the benefit of placing the piece in the newly discovered location is worth the cost of all the extra actions necessary to get the piece into the superior position.

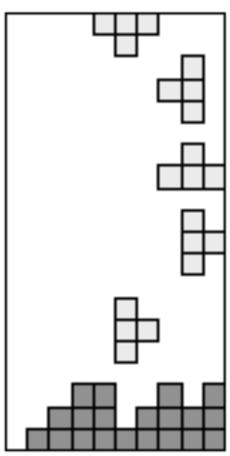

Figure 2: Complementary action or goal switching?

Unfortunately, the line that distinguishes genuine complementary actions from goal-switches is very fuzzy and difficult to measure. In Figure 2, the accumulation is the same as it is in Figure 1, but in this example the piece is rotated first and translated all the way to the right wall of the gameworld, then translated three spaces to the left. Did the player do this as a complementary action intended to save the perceptual effort of verifying whether the rotated piece was lined up with the appropriate place in the accumulation, or did the player first decide to place the piece in the rightmost position and then change the plan upon realizing that there was a better place for the piece to go? This kind of situation, also very common in *Tetris*, is difficult to classify.

[2] Points are gained in Tetris by eliminating lines. A line is eliminated when all 10 of its spaces are filled by zoids. Eliminating multiple lines at one time results in bonus points with the largest bonus being given for a *Tetris*, which is the elimination of 4 lines at once.

Classifying Complementary Actions

Complementary actions in Tetris may take the form of either rotations or translations. A complementary translation may be one in which the player utilizes the wall to verify the vertical position of a piece. A complementary rotation may be one in which the player rotates the piece freely in order to directly compare its contours to the accumulation below. Neither of these actions contributes to the pragmatic plan of getting the piece from its start position to its destination, but both do potentially aid the player by lightening their cognitive load or increasing their accuracy.

Given that there is some debate as to where to draw the line between complementary actions and goal-switching or errors, we have devised criteria for determining if translation and rotation actions are complementary. The three criteria of translation actions differ in their strictness. In contrast, the two criteriq for rotations classify different categories of rotation actions.

Translation Criteria: We call a translation action complementary if:

- Lenient translation criterion: Both a left translation and a right translation occur during any single episode.
- Medium translation criterion: A zoid has been translated all the way to one wall and then changes direction.
- Strict translation criterion: A zoid is translated all the way to one wall and subsequently moved no more than 3 spaces away from that wall.

The lenient criterion operates under the assumption that a pragmatic action plan would never include more than one direction of translation. This criterion will include a large number of small slips and indecisiveness of the player along with some number of genuine complementary actions.

The medium criterion assumes that the player is in fact using the wall for counting purposes, as they have not placed the piece along that wall. This criterion avoids the inclusion of simple slips and indecisiveness by the player, but will still include strategy changes such as those in Figure 1.

The strict criterion carries the same assumptions as the medium criterion, but also attempts to exclude strategy changes on the premise that translating to the wall on the side of the field opposite of the zoid's final destination is unlikely to be epistemically useful, and more likely to be a mid-episode change of strategy.

Rotation Criteria: Rotations are complementary if the zoid has been in any unique orientation more than once during an episode. There are two categories of rotation:

- Category 1 – *Both-Rotations*: During any episode, the zoid rotates both clockwise and counter-clockwise

- Category 2 – *Over-Rotation*: During any episode, a zoid rotates in one direction more than 3 times (for a J, L, or T zoid), more than 1 time (for a Z, S, or I zoid), or at all (a square zoid).

The both-rotations criterion assumes that a player using both rotation directions in a single episode cannot be adhering to a purely pragmatic plan, as the piece has surpassed and subsequently backtracked to its final orientation. The over-rotation criterion is based on the idea that there is no pragmatic use in continuing to rotate a zoid past the number of unique orientations of that zoid type, as the orientation needed for its final placement would have certainly been surpassed. It seems likely that both rotational criterion will include errors, indecisiveness, strategy-changes, as well as instances of complementary actions.

Any rotation of the square zoid is futile, given that it only has one unique orientation. Such a rotation action would appear to be neither pragmatic nor complementary in nature, and almost certainly an error. However, given the definition of complementary actions used here and the relative infrequency of any instances of square rotations, we have included them in the analysis.

The Study

We held two *Tetris Tournaments* for cash prizes in two successive years at a local convention for fans of science fiction, fantasy literature, Japanese anime, and video games. The rules of the tournament were as follows: Anyone who wished to enter would first compete through a qualifying round. Every entrant played two games of *Tetris*, keeping the higher of the two scores earned (approximately 60% of participants scored higher in their second game). When the qualifiers closed, the top eight competitors then had to compete in a single-round elimination match (#1 vs. #8, #2 vs. #7, etc.). Each match featured the two competitors playing side by side, the higher scorer winning the match and proceeding to the next round. After the tournament, as a condition of entry, the top 3 winners came to our laboratory to play as many games of *Tetris* as they could in one hour while an eye-tracking system recorded their eye movements for use in further research.

The version of *Tetris* that we used is a custom port, written in Flash, that emulates the graphics, sound, controls, and scoring system of the 1989 Nintendo Entertainment System™ version of the game, with the added feature of logging the state of the gameworld every frame. This allows for detailed analysis and perfect playback of each game recorded. In total, we have collected data for 173 complete games from 59 different players.

Player Expertise and Counting Complementary Actions

As all 59 players played the two games of the qualifying

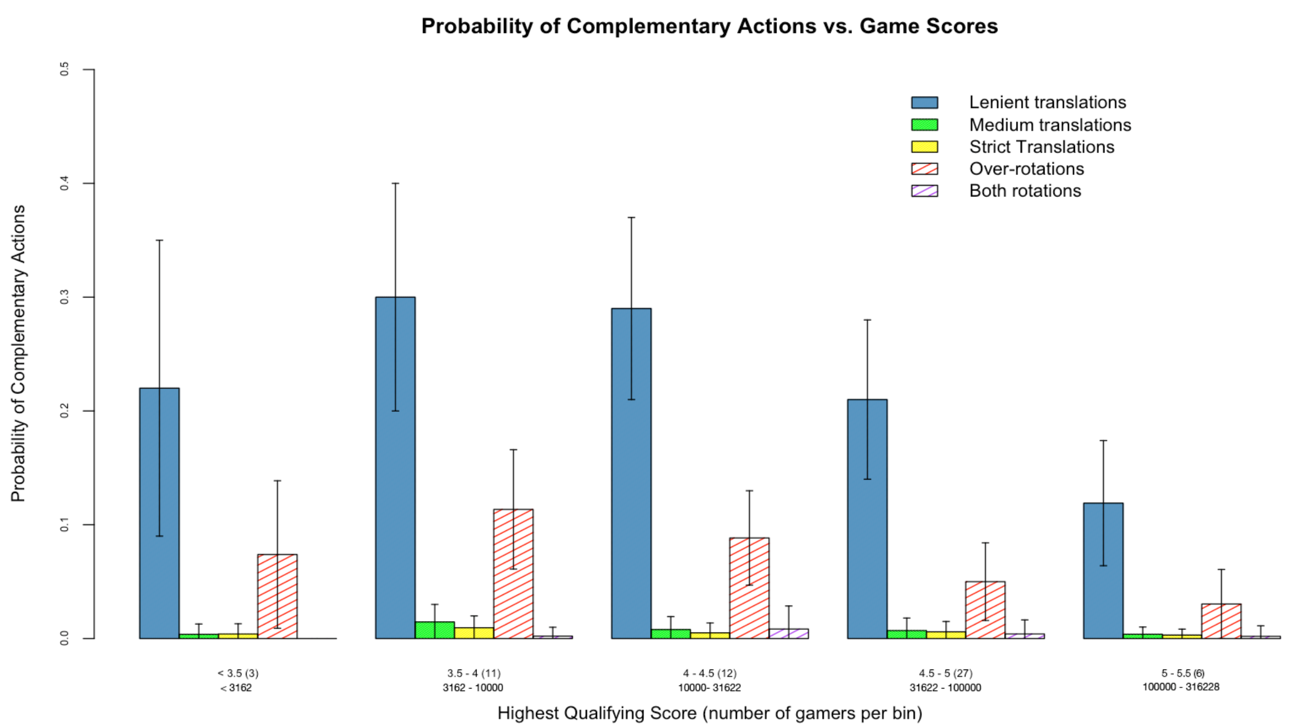

Figure 3: Use of Complementary Actions Decreases with Expertise. Each of the 59 players is classified into a half-logarithm score bin based on the highest game played during the tournament qualification round of two games. For each player each criterion in each of the two sets of criterion (translations and rotations) is calculated based on episodes collected across all games played. Error bars show +/- 1 standard deviation.

round under the same conditions, we used their top score from that round as a measure of expertise. These 59 top scores ranged from a low of 867 to a high of 236,305. As the distribution of scores seemed approximately logarithmic we created five ½ log bins ranging (all logs to base ten) from < 3½ (under 3162 points), 3½-4 (up to 10,000 pts), 4-4½ (up to 31,622 pts), 4½-5 (up to 100,000 pt), and 5-5½ (up to 316,228 pts). As show by the abscissa labels in Figure 3, the distribution of players to these bins was uneven with the greatest concentration of players in the middle three bins.

The criteria used for Tetris expertise in the Kirsh and Maglio papers is seldom mentioned. In Maglio and Kirsh (1996) they report data from two players who played for 20 hours each. Although our inference is indirect, we conclude from this source that even after 20 hours of practice, Maglio and Kirsh's players were at the approximate skill level of our first and second bin of players and well below the skill level of our other bins of players. Our best player's best game was over 1 million points and for 25 (out of 173) of the games we collected the score was over 100,000 points.

For each of our players, we calculated the probability that one of their episodes would contain a complementary action according to each criterion in our two sets of criteria. In counting the rate of complementary actions, we included episodes from all games played by each player. As the best 8 players each year were involved in the single-round elimination matches, and the best three players from each year played an hour's worth of Tetris in our laboratory, this means that we have the most data, and therefore the most stable estimate of complementary actions, from our most expert players.

Results

Our results are shown in Figure 3. The plot represents episode data obtained from 173 games of Tetris – 118 of which were captured during the two qualification games for the tournaments and 55 during the playoffs or at the subsequent laboratory sessions for the top three tournament players (six players across two years of tournaments).

Players were assigned to bins based on the best score out of two games played in their qualifying round. These half-log bins and the scores that they encompass are represented along the abscissa. The total number of players in each bin is shown in parentheses next to each bin's label. The ordinate shows the probability that a complementary action occurred in any given episode according to the five criteria we considered: lenient, medium, and strict translation criteria (the solid bars in Figure 3); and over-rotations and both-rotations criteria (the striped bars in Figure 3).

The most lenient translation criterion, being whenever a player made both a left and right translation, is satisfied the most frequently. Unfortunately, this criterion also captures much suboptimal behavior on the part of the player, including slips, indecisiveness, or changing of strategy mid-episode. Note the inverted-U shape to the occurrences of these actions. Initially, as player skill (total score) increases, these complementary actions rise in frequency, but quickly show marked drop-off as intermediate skill levels are approached. Even according to this very lenient interpretation of what constitutes a complementary action, their frequency is minimal in our most highly skilled players.

The medium and strict translation criteria, met when a piece is translated to one wall and back, are satisfied altogether much less frequently. The actions captured by these criteria are less likely to include slips, indecisiveness, or strategy change than does the lenient criteria. According to these more realistic classification criteria, no player scoring over 100,000 points used complementary translation actions in more than 2% of all episodes.

Over-rotation actions are classified as any rotation beyond what was necessary to place the piece in its final location. The inverted-U shape seen in the lenient complementary translation scores holds here as well, with over-rotation actions first increasing, and then becoming less and less frequent with increased overall score. Both-rotations actions were exceedingly rare, but also show this pattern.

One player scored 1,023,941 points in a single game (scoring 108,508 points in his qualifying round), a highly uncommon event. On this game, the player exhibited the lowest number of lenient criterion translational complementary actions (probability 0.08) of any other player, with no instances of medium or strict translational actions. He scored 1 over-rotation and 5 both-rotations out of 1,281 episodes (probabilities of 0.0008 and 0.0039 respectively).

These criteria for classifying when a complementary action may have occurred do not indicate that such an action, in fact, has occurred. What they do provide is a narrowing down of episodes to only those in which a complementary action was possible. Our strict translation and both-rotation criteria would seem to damage the claim that complementary actions increase with expertise.

The lenient translation criteria and the over-rotation category show the same inverted-U function. Although both of these seem likely to include motor slips, indecisiveness, or changes in strategy, they might suggest that complementary actions might be a stage that players pass through on their road to expertise. However, regardless of how we look at our data they do not suggest that complementary actions are an integral part of expertise..

Conclusions

In Tetris, scores accumulate with game play: the better the player, the longer the game, the higher the score. Our best players played the most games and played each game longer. These factors assure that the rate of complementary actions extracted from the data of our best players is also the most reliable. As even by our most lenient criteria we find that the use of complementary actions all but disappears as expertise increases, we believe that our claim that expert Tetris players engage in very few complementary actions is rock solid.

In contrast to our data are the various studies by Kirsh and Maglio in which people with very little or no prior experience in Tetris were recruited. In some of these studies the players were given up to 20 hours of practice.

Although it is impossible to estimate precisely from the published reports, we believe that after 20 hours of practice Kirsh and Maglio's players would score comparably with our second bin (up to 10,000 points per game). This expropriation would make their data compatible to ours and would seem to support conclusions drawn from our lenient transposition criterion and our over-rotation category that complementary actions exhibit an inverted-U shaped function that starts low, peaks at moderate levels of skill development, and rapidly declines as expertise is approached. This function would be consistent with work by Neth (2004), which shows that as expertise increases complementary actions provide diminishing returns.

The inverted-U also would be compatible with expectations from the soft constraints hypothesis (Gray & Fu, 2004; Gray, et al., 2006), which leads us to expect a type of embodied cognition that is neutral to the source of information (actions in-the-world or processes in-the-head), choosing among alternative sources on a cognitive cost-accounting basis.

Unfortunately for the complementary action hypothesis, the number of goal-switches might also show an inverted-U function. Beginners are often focused on the mechanics of game play, not the strategies. As the mechanics are mastered, each episode of play becomes more goal-directed but better goals may be discovered during an episode and, if so, goal-switches should increase. Our future reports will attempt to use eye data to distinguish goal-switch induced actions from true complementary actions and slips.

These questions of interpretation may yield to criteria that distinguish complementary actions from slips and changes in player intentions. With better criteria in hand, we can then ask questions such as (a) what an inverted-U function tells us about the role of complementary action in learning to play and maximizing performance and (b) do complementary actions interfere with the acquisition of expertise or do they help make one an expert more quickly than if they were not used?

Author Notes

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