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An Experimental Test of a Collective Search Model*

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Abstract

This paper's objectives are to design laboratory experiments of finite and infinite sequential collective search models and to test some implications obtained in the model of Albrecht, Anderson and Vroman (2010) (the AAV model). We find that, compared with single-agent search, the average search duration is longer in collective search with the unanimity rule, but it is shorter in the case of collective search in which at least one vote is needed to stop searching. In addition, according to estimates from round-based search decisions, subjects are more likely to vote to stop searching in collective search than in single-agent search. This confirms that agents are less picky in the case of collective search. Overall, the experimental outcomes are consistent with the implications suggested by the AAV model. However, a different outcome is obtained from the AAV model in terms of the size order of the probabilities of voting to stop searching in collective search for the various plurality voting rules.

JEL classification: C91, D83

Keywords: experiment, collective search, voting rule.

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1 Introduction

An agent's decision mechanism regarding whether to stop searching has been considered in many economics fields, including labor economics, monetary economics, macroeconomics, industrial organization, and others. In recent years, there has been a new trend of interest in collective search, in which a decision is determined by a group consisting of multiple agents, rather than a single agent. There is a theoretical literature that analyzes the properties of decision-making in the case of collective search (Albrecht, Anderson, and Vroman, 2010; Compte and Jehiel, 2010). However, to the best of our knowledge, no empirical studies on this new topic have been conducted because it is difficult to collect data on collective search. This paper is the first attempt to provide experimental evidence about collective search and to test the theoretical implications obtained in the collective search model constructed by Albrecht, Anderson, and Vroman (the AAV model hereafter). Overall, we find that experimental outcomes are consistent with the main implications obtained in the AAV model.

In the AAV model, a group engages in a search activity to fill a vacant position, or a family looks for a new house together. The members of the group or family make the decision on whether to hire a newly encountered worker or to purchase a house by voting. The AAV model assumes that members are homogeneous with respect to preferences and that each member draws a value from an identical and independent distribution across members. It focuses on a comparison of the member's reservation value between single-agent search and collective search in an environment where the drawn value differs among the members under various plurality voting rules. The main predictions of the AAV model are that members are less picky in collective search than in standard single-agent search, in the sense that each member's threshold is lower, and that the members' thresholds vary with the voting rules.

In recent years, many articles have been devoted to experimental studies of the single-agent search model (Cox and Oaxaca, 2009; Harrison and Morgan, 1990). The experimental task is tractable and attractive for testing the implications of sequential search models. The search environment characterized fully in the model is usually far removed from the environment observed from the micro data. Therefore, the search environment characterized in the model cannot be duplicated perfectly using the micro data. However, we can create this search environment in the laboratory by controlling treatments. Experimental studies on the sequential search model have definitely become widespread, covering various topics such as the effect of unemployment benefit sanctions on an individual's search behavior (Boone, Sadrieh, and van Ours, 2009) and the difference in individuals' search behavior by their attitudes toward loss and risk (Schunk, 2009). Schunk and Winter (2009) find that, in many studies, agents stop searching earlier than the theoretically optimal level, and explore the reason for this result.

We expand upon this research, in that this paper focuses on the decision-making process of multiple agents in a search activity. The main feature of our experimental design is that three types of games are conducted to identify exactly the predictions of the AAV model where agents are assumed to be homogeneous with respect to preferences. Game A is a benchmark of a standard single-agent search task, Game B is a collective search task where three group members have the common value drawn from a distribution, and Game C is a collective search task where three group members each draw different values from the same distribution.[1] The difference between Game A and Game B is attributable to heterogeneity among members with respect to their attitudes toward risk and loss and other unobserved factors.[2] The difference between Game A and Game C arises from the heterogeneity among members mentioned above, plus uncertainty, in the sense that no member knows what value the other members draw. Therefore, the difference-in-difference between the above two differences is caused only by the uncertainty among members, in that the values drawn by other members are unknown, similarly to the AAV model. In addition, we design three subgames in Games B and C: subgame 1 adopts the plurality voting rule that the collective search activity is stopped only if at least one member votes to stop searching (the one-vote rule); subgame 2 is characterized by the fact that the collective search activity is stopped only if at least two-thirds of members vote to stop searching (the majority rule); and subgame 3 establishes that the collective search activity is stopped only if all members vote to stop searching (the unanimity

[1] This implies that each member draws a value from the independent and identical distribution.

[2] Heterogeneity of preferences among members in a group is ruled out in the AAV model.

rule). These subgames provide the evidence about the effect of voting rules.

We conducted experimental tests of two different search models at two universities: a finite sequential search model at Osaka University, and an infinite sequential search model with a 5% death probability at Hokkaido University. Neither model allowed subjects to recall values that they had already drawn. At both universities, subjects were noneconomics-major undergraduate and graduate students.

In this experiment, we focus on exploring (1) the search duration and (2) the probability of voting to stop searching in collective search with various plurality voting rules compared with single-agent search. Our finding regarding the first focus is that, compared with single-agent search, the average search duration is longer in collective search with the unanimity rule but shorter in collective search with the one-vote rule in both the infinite and the finite sequential search models, controlling for heterogeneity of risk and loss attitudes, and unobserved factors among group members. These results are consistent with the implications of the AAV model. The relationship of search duration between single-agent search and collective search with the majority rule is statistically unclear in both models according to our experiments. According to our experimental outcomes, two effects operate to determine this relationship. It takes more time to reach an agreement in collective search with the majority rule than it does in single-agent search. Thus, on the one hand, the collective search structure with the majority rule lengthens the search duration. However, on the other hand, it lowers each subject's reservation value because she or he is less picky, thereby shortening the search duration. Under the majority rule, these opposite effects are canceled out, resulting in the conclusion that there is no difference in search duration between single-agent search and collective search with the majority rule. This outcome is not surprising because the numerical exercise using the theoretical model (shown later) illustrates a similar result.

The second focus is on identifying differences in a subject's willingness-to-accept between single-agent search and collective search. To do this, we estimate a probit model to examine the determinants of the probability of voting to stop searching, using data from every round-based decision regarding whether to vote to stop searching. Our findings are that subjects are more likely to vote to stop searching in collective search than in single-agent search, and that this outcome is most strongly observed in collective search with the majority rule in the infinite sequential search model, and with the unanimity rule in the finite sequential search model. These estimated results first confirm the threshold effect referred to by the AAV model, in the sense that subjects lower their reservation value in collective search. However, our experimental outcome differs from the AAV model's prediction in terms of the size order of the reservation values between the types of collective search with the various plurality voting rules. This difference arises from the subjects' preferences regarding the two negative externalities (one externality is that collective search continues despite a subject's preference to stop searching, and another externality is that collective search stops despite the subject's intention to continue searching). According to the estimates of the finite sequential search model, we find that subjects are more likely to vote to stop searching in collective search with the unanimity rule than in one with the one-vote rule, which is the opposite situation to the one that occurs in the numerical exercise based on the theoretical model. This result implies that a subject who actually participated in this experiment is more averse to incurring disutility caused by the negative externality whereby collective search continues despite the subject's preference to stop searching than we would expect from the numerical exercise based on the theoretical model with a risk neutral agent.

In summary, overall, the experimental outcomes are consistent with the implications suggested by the AAV model in terms of the relationships of the search duration and the probability of voting to stop between collective search and single-agent search. However, we obtain different outcomes in terms of the relationships of the probability of voting to stop in the collective search activities among plurality voting rules.

In addition, there are other interesting findings in the comparisons of the effects of Games B and C on the probability of voting to stop searching. The probit estimates show that many coefficients on Games B are significantly positive and different from zero, relative to the reference group of Game A. This implies that subjects are not homogeneous with respect to their preferences regarding risk, loss and unobservables, and that uncertainty, in terms of heterogeneity of preferences among members, lowers each member's reservation value. Because the coefficient on each Game C is significantly positive as well, there exists an additional uncertainty in that each member does not know what value other members draw, which reinforces the incentive to vote in an earlier round to stop searching.

This paper is organized as follows. In Section 2, we discuss the implications of the AAV model in more detail. Section 3 explains the strategy of identification, and the experimental design is explained in Section 4. The descriptive statistics of this experiment and the results of the regression analysis are shown in Section 5. The final section provides concluding remarks.

2 Model

Albrecht, Anderson, and Vroman (2010) construct a collective search model in which group members decide to stop or continue searching through voting. They assume that group members are risk neutral and homogeneous with respect to preferences and that each member randomly draws a value from an independent and identical distribution across members. It should be noted that values are uncorrelated across group members. This model setup is a proxy describing the more realistic environment in which members draw the same value but do not know how other members evaluate the value and/or their attitudes toward loss and risk.[3] This setting may differ from a realistic situation, but it is analytically tractable and qualitatively indifferent. Given the value in hand, each group member votes for or against stopping the search.

The authors find that agents are less picky in the case of collective search than single-agent search because each member faces the following two negative externalities: (i) collective search continues under a given voting rule despite the preference of an individual subject for search to stop; and (ii) conversely, collective search stops under a given voting rule despite the subject's preference to continue searching. These negative externalities are attributable to the assumptions that each member draws a value from the independent and identical distribution, and that other

[3] Compte and Jehiel (2010) consider the case where members hold the same value but do not know how other members evaluate the value.

members' values are unknown. Thus, the reservation value is lower in collective search than in single-agent search, thereby leading to a shorter search duration (a higher probability of stopping the search). This is referred to as the *threshold effect* according to the AAV model. However, there is another effect determining the search duration; that is, collective search with plurality voting rules either raises or lowers the probability of the search stopping, given any reservation value. This is referred to as the *vote aggregation effect*. Whether the probability of stopping the search for any given reservation value is higher or lower in collective search than in single-agent search depends on the given reservation value in the single-agent search structure or the discount factor, and the plurality voting rules.[4]

Figure 1 illustrates an example of the AAV model and decomposes the probability of stopping the search in the case of single-agent search versus collective search into the two effects, i.e., the threshold and the vote aggregation effects. We assume that an individual agent conducts a collective search activity with other two members and faces a uniform distribution $F(x)$ with a lower bound of $\underline{x}$ and an upper bound of $\overline{x}$. The probability of continuing to search $P(x, 3, i)$ is calculated by the sum of the binomial probabilities that exactly $i - 1$ or fewer among three members vote to stop, given that the reservation value is x. For example, $P(x, 3, 2)$ indicates the probability that none or only one of three members votes to stop, in which case this group continues to search under the majority rule. Be aware that $P(x, 1, 1) \equiv F(x)$. $(1 - P(x, 3, i))$ instead represents the probability of stopping the search. In this illustration, the reservation value is lower in collective search with the majority rule (x_c) than in single-agent search (x_s), and the probability of stopping the search is higher in collective search with the majority rule $(1 - P(x_c, 3, 2))$ than in single-agent search $(1 - P(x_s, 1, 1))$. The difference in the probability of stopping the search between collective search with the majority rule and single-agent search is decomposed into the threshold effect $(P(x_s, 3, 2) - P(x_c, 3, 2))$ and the voting aggregation effect $(P(x_s, 1, 1) - P(x_s, 3, 2))$.

The vote aggregation effect results in a higher probability of stopping the search in collective

[4]The reservation value and the discount factor are closely related in the standard sequential search model. If an agent discounts the future more, then the agent's reservation value is lower, implying that he or she wants to exit the search earlier.

search with the one-vote rule than in single-agent search for any given reservation value (see Figure 2). Because the collective search activity ceases if any of the three members votes to stop, the probability of stopping the search is higher. This reinforces the shorter search duration that occurs for this type of search. On the other hand, in a comparison of single-agent search versus collective search with the unanimity rule from Figure 3, the vote aggregation effect induces a lower probability of stopping the search in the case of the collective search activity for any given reservation value because it takes more time for the three members to reach an agreement. Thus, this type of search leads to a longer search duration. Under the unanimity voting rule, the vote aggregation effect is large enough to dominate the threshold effect, thereby resulting in the longer search duration. Comparing single-agent search with collective search under the majority rule, the vote aggregation effect reinforces the threshold effect within the range of lower reservation values (or lower discount factor), implying a shorter search duration. The vote aggregation effect has the opposite effect to the threshold effect within the range of higher reservation values (or higher discount factor). For sufficiently high reservation values, the threshold effect is dominant over the vote aggregation effect, leading to a shorter search duration; however, for only moderately high reservation values, the magnitude relation of these two effects is in reverse, resulting in a longer search duration.

3 Strategy for identification

This section considers a methodology to identify the implications of the AAV model. In this experiment, we restrict ourselves to the case where the group consists of three members.

3.1 A single-agent search model versus a collective search model

This subsection explains a way of testing and comparing a single-agent search model versus a collective search model with various plurality rules. Recall that in the AAV model, agents are homogeneous with respect to risk and loss attitudes and preferences, and that the difference between single-agent and collective search behaviors arises from uncertainty, in the sense that values drawn by other members are unknown. In this experiment, however, there exists another source of uncertainty, in the sense that no group member knows the risk and loss attitudes of the other members. To eliminate the latter uncertainty, we conduct the following three games.

- **Game A:** A single agent independently decides to stop or continue searching.
- **Game B:** A group draws a common value from the distribution (group members know that they hold the same value), and then the group members collectively decide to stop or continue searching throughout voting.
- **Game C:** Each member of a group draws a value from the independent and identical distribution (the drawn values are identically independent across group members), and then the group members collectively decide to stop or continue searching throughout voting.

From these games, the search duration of each subject can be observed. The difference in the search duration between Games A and B is attributable to the uncertainty about other members' attitudes toward risk and loss and unobserved characteristics. On the other hand, the difference in the search duration between Games A and C is attributable to two types of uncertainty: uncertainty in terms of what other members' attitudes toward risks and loss and unobserved characteristics are, as mentioned above, and of what value other members draw from the distribution. Therefore, the difference-in-difference of the search duration between the above two differences is derived only from the uncertainty in terms of what value the other members draw, implying that the uncertainty in terms of different risk and loss attitudes and individual characteristics among the members is eliminated. This method picks up the exact difference in the search duration between single-agent search versus collective search as characterized by the AAV model.

3.2 Comparisons of different plurality voting rules

The AAV model shows that the probability of stopping the search in collective search varies according to the plurality voting rules that apply. To identify the effects of different plurality voting rules, we conduct the three subgames below.

- **Subgame 1:** The collective search activity is stopped only if at least one member of the group votes to stop (the one-vote rule).
- **Subgame 2:** The collective search activity is stopped only if two-thirds or more of the members of the group vote to stop (the majority rule).
- **Subgame 3:** The collective search activity is stopped only if all members of the group vote to stop (the unanimity rule).

In subgame 1, members are faced with the risk that collective search will stop despite an individual member's preference to continue searching, whereas in subgame 3, collective search continues even if an individual member wants to stop searching. Subgame 2 is the in-between case of subgames 1 and 3. Then, we can identify the effects of these above risks exposed by the different plurality voting rules.

4 Experimental design

Our experiments were conducted in the experimental laboratory of the Institute of Social and Economic Research at Osaka University and the Center for Experimental Research in Social Sciences at Hokkaido University. The experiments consisted of three sessions at Osaka University and four sessions at Hokkaido University for reasons relating to laboratory capacity. Each session involved the same eight games (two games of Game A and three subgames each for Game B and Game C). We conducted experimental tests of two different search models at the two universities; at Osaka University, each game contained 20 rounds in a finite sequential search model, whereas at Hokkaido University, an infinite sequential search model with a 5% death probability was designed in each game. Recall was not allowed in either model. Although subjects are not encouraged to search for longer in a search environment where recall is not allowed, this design is simple and exactly duplicates the AAV model's structure. The infinite sequential search model is used to test the implications of the AAV model directly. The finite sequential search model, on the other hand, differs from the AAV model in terms of the way each search activity is terminated, but it is more realistic and more easily understandable for subjects in terms of the experimental structure of the search activity.[5] We design the two different search models and compare the experimental results.

The games differ in terms of the treatments in each experimental session. The experimental processes with the different treatments for single-agent and collective search are set out below.

4.1 Game A: Single-agent search

Game A is a benchmark of a normal single-agent search task. A subject draws a value from a uniform distribution with a lower bound of zero and an upper bound of 3000. After the value is drawn, the subject decides whether to stop or continue searching. If the subject chooses to continue, he or she moves to the next round and then again draws a value from the same distribution.

We begin with an infinite sequential search model. The value of searching for a single agent V_A is given by:

$$V_A = \underbrace{(1-\delta)F(R_A)V_A}_{\text{continuing search}} + \underbrace{\delta\int_0^{R_A} xdF(x)}_{\text{terminating search}} + \underbrace{\int_{R_A}^{3000} xdF(x)}_{\text{accepting the offer}},$$

where δ represents an exogenous probability of death, R_A is the reservation value, and $F(x)$ represents a uniform distribution. For simplicity, there is no discount over rounds, which encourages subjects to search longer. Our experiments set the death probability at 0.05, implying that a subject's search activity has to be terminated coercively with a probability of 5% for each round. The sum of the first two terms on the right-hand side represents the value of rejecting a drawn offer. The first of these two terms is the value of continuing the search after the subject survives to the next round, and the second of these terms indicates the value of the search activity being terminated after the offer is rejected. When a search activity is coercively terminated, the subject

[5] Because the probability of death is 0.05 in the infinite sequential search model, the expected number of rounds that a subject can search is 20, which is the same as the maximum number of rounds in the finite sequential search model.

has no choice but to accept the value that she or he rejects in the previous round.[6] The final term represents the value of accepting a drawn offer. Because the reservation value of gaining R_A is equivalent to the value of searching in the next round ($R_A = \delta R_A + (1-\delta)V_A$), we obtain $R_A = V_A$.

As in the standard model with finite sequential search, the reservation value R_t^A in round t is given by:

$$R_t^A = \underbrace{F(R_{t+1}^A)R_{t+1}^A}_{\text{continuing search}} + \underbrace{\int_{R_{t+1}^A}^{3000} x dF(x)}_{\text{accepting the offer}}.$$

It consists of the value of continuing the search and the value of accepting a drawn offer. If the subject continues searching up to 20 rounds, then he or she automatically has to choose to stop searching.

4.2 Game B: Collective search with a common value

Game B deals with collective search in which all members of a group draw a common value from the uniform distribution with a lower bound of zero and an upper bound of 3000, and they know that they have the same value. Whether collective search stops or continues is determined by voting by group members. Because group members are randomly reshuffled in every game, no member knows who the other two group members are. Therefore, this rules out the presence of a learning effect regarding other group members' voting behavior.

If group members are homogeneous with respect to preferences, as in the AAV model, the collective search model with a common value is reduced to the single-agent search model shown in Game A. Therefore, the value for a group member of collectively searching in the finite sequential search model V_B is:

[6] The experiment is designed to reduce the loss that the subject would have incurred if the search was terminated after she or he decided to continue to search. It encourages the subject to search longer. In other words, if we design that the subject does not receive any payment when the search activity is terminated coercively, then it is expected that she or he does not engage in the search activity for many rounds.

$$V_B = \underbrace{(1-\delta)F(R_B)V_B}_{\text{continuing search}} + \underbrace{\delta\int_0^{R_B} xdF(x)}_{\text{terminating search}} + \underbrace{\int_{R_B}^{3000} xdF(x)}_{\text{accepting}}.$$

Because $R_B = \delta R_B + (1-\delta)V_B$, we obtain $R_B = V_B$. If all the group members are homogeneous with respect to preferences, they all either accept or reject a drawn value, regardless of which voting rule is employed.

In addition, in the finite sequential search model, the collective search model is reduced to the single-agent search model. Hence, the reservation value of collective search with a common value is obtained:

$$R_t^B = \underbrace{F(R_{t+1}^B)R_{t+1}^B}_{\text{continuing search}} + \underbrace{\int_{R_{t+1}^B}^{3000} xdF(x)}_{\text{accepting the offer}}.$$

If there is a difference in the reservation values between Games A and B in our experiment, it is attributable largely to the heterogeneity of preferences to search activity across members. In our experiment, Game B consists of three subgames, each of which differs according to the plurality voting rules explained in Section 3.2.

4.3 Game C: Collective search with different values

In Game C, similarly to Game B, whether collective search stops or continues is determined by voting by group members. Unlike Game B, however, each group member separately draws a value from a uniform distribution with a lower bound of zero and an upper bound of 3000, which means that drawn values are identically independent across the group members. In our experiments, Game C, like Game B, consists of three subgames, C-1, C-2, and C-3, as explained in Section 3.2.

As above, we begin with the infinite sequential search model. Suppose that collective search is stopped if at least one group member votes to stop searching (subgame C-1: one-vote rule). The value for a subject of collectively searching V_{C1} is given by:

$$
\begin{aligned}
V_{C1} \quad = \quad & \underbrace{(1-\delta)F(R_{C1})^3 V_{C1}}_{\text{continuing collective search}} + \underbrace{\delta F(R_{C1})^2 \int_0^{R_{C1}} xdF(x)}_{\text{terminating collective search after voting to continue}} \\
& + \underbrace{\int_{R_{C1}}^{3000} xdF(x)}_{\text{accepted by self and/or others}} + \underbrace{[1-F(R_{C1})^2]\int_0^{R_{C1}} xdF(x)}_{\text{accepted by one or both of the others, but not by self}} .
\end{aligned}
$$

The sum of the first two terms on the right-hand side represents the value of collective search because all group members vote against stopping the search. Of these two terms, the first term denotes that the collective group survives to the next round with a probability of $(1-\delta)$, but the second term shows that the group has to stop searching, and thus obtains the value drawn in the previous round. The sum of the third and fourth terms indicates the value for the subject of accepting a drawn offer. The third term represents that at least one member, including the subject herself or himself, votes to stop searching, and the fourth term shows that one or both of the other two members votes for stopping the search, although the subject herself or himself votes against it. Because $R_{C1} = \delta R_{C1} + (1-\delta)V_{C1}$ according to the reservation value rule, we obtain $R_{C1} = V_{C1}$.

The finite sequential search model is more simple and straightforward. The reservation value of collective search under the one-vote rule can be derived in a similar manner.

$$
R_t^{C1} = \underbrace{F(R_{t+1}^{C1})^3 R_{t+1}^{C1}}_{\text{continuing collective search}} + \underbrace{\int_{R_{t+1}^{C1}}^{3000} xdF(x)}_{\text{accepted by self and/or others}} + \underbrace{[1-F(R_{t+1}^{C1})^2]\int_0^{R_{t+1}^{C1}} xdF(x)}_{\text{accepted by one or both of the others, but not by self}} .
$$

The difference between these two equations is that the value term indicating the termination of collective search included in the infinite sequential search model is excluded from the value function of the finite sequential search model.

Next, we consider a collective search model in which collective search is stopped only if at least two out of three members vote to stop searching (subgame C2: majority rule). The value for a subject of collectively searching in the infinite sequential search model V_{C2} is obtained as follows:

$$
\begin{aligned}
V_{C2} \;=\; & \underbrace{(1-\delta)[F(R_{C2})^3+3(1-F(R_{C2}))F(R_{C2})^2]V_{C2}}_{\text{continuing collective search after voting to continue}} \\
& \underbrace{+\delta[F(R_{C2})^2+2(1-F(R_{C2}))F(R_{C2})]\int_0^{R_{C2}} xdF(x)}_{\text{terminating collective search after voting to continue}} \\
& + \underbrace{\delta F(R_{C2})^2\int_{R_{C2}}^{3000} xdF(x)}_{\text{terminating collective search after voting to stop}} \quad \underbrace{+[1-F(R_{C2})]^2\int_0^{R_{C2}} xdF(x)}_{\text{accepted by others, but not by self}} \\
& + \underbrace{[1-F(R_{C2})^2]\int_{R_{C2}}^{3000} xdF(x)}_{\text{accepted by self and one or both other members}} \quad .
\end{aligned}
$$

The first term on the right-hand side shows the value of continuing the collective search activity after the collective team survives to the next round. $[F(R_{C2})^3 + 3(1 - F(R_{C2}))F(R_{C2})^2]$ implies the probability that at least two members vote against stopping the search. The second and third terms represent the value of the collective search activity being coercively terminated. The second term shows a case in which at least two members, including the subject herself or himself, vote against stopping the search before termination of the collective search activity, whereas the third term deals with the case in which the subject herself or himself votes for stopping the search, but the other two members vote against it before termination. The fourth and fifth terms indicate the value for the subject of stopping the collective search; the fourth term shows a case in which the subject votes against stopping the search, but the other two members vote for it, whereas the fifth term indicates that the subject herself or himself and one or both of the other two members vote to stop searching. As mentioned before, recall that $R_{C2} = V_{C2}$.

The reservation value of collective search in the case of the finite sequential search model is obtained in a similar manner.

$$
\begin{aligned}
R_t^{C2} \quad = \quad & \underbrace{[F(R_{t+1}^{C2})^3 + 3(1 - F(R_{t+1}^{C2}))F(R_{t+1}^{C2})^2]R_{t+1}^{C2}}_{\text{continuing collective search}} \\
& + \underbrace{[1 - F(R_{t+1}^{C2})]^2 \int_0^{R_{t+1}^{C2}} x dF(x)}_{\text{accepted by the others, but not by self}} + \underbrace{[1 - F(R_{t+1}^{C2})^2] \int_{R_{t+1}^{C2}}^{3000} x dF(x)}_{\text{accepted by self and one or both of the others}} \quad .
\end{aligned}
$$

Finally, we move to a collective search model in which collective search is stopped only if all members of the group vote to stop (subgame C3: unanimity rule). The value for a subject of collectively searching in the infinite sequential search model V_{C3} is given by:

$$
\begin{aligned}
V_{C3} \quad = \quad & \underbrace{(1 - \delta)[1 - (1 - F(R_{C3}))^3]V_{C3}}_{\text{continuing collective search}} \\
& \underbrace{+\delta[F(R_{C3})^2 + 2(1 - F(R_{C3}))F(R_{C3}) + (1 - F(R_{C3}))^2] \int_0^{R_{C3}} x dF(x)}_{\text{terminating collective search after voting to continue}} \\
& \underbrace{+\delta[F(R_{C3})^2 + 2(1 - F(R_{C3}))F(R_{C3})] \int_{R_{C3}}^{3000} x dF(x)}_{\text{terminating collective search after voting to stop}} + \underbrace{[1 - F(R_{C3})]^2 \int_{R_{C3}}^{3000} x dF(x)}_{\text{accepted by all members}}.
\end{aligned}
$$

The first term on the right-hand side represents the value for the subject of continuing the collective search after her or his collective team survives to the next round, whereas the last term denotes the value for the subject of accepting a drawn offer when all the members vote to stop the search unanimously. The second and third terms represent the value of the collective search activity being coercively terminated. The second term indicates the value of the collective search activity being terminated after at least the subject herself or himself votes against stopping the search. In the third term, collective search is terminated after at least the subject herself or himself votes for stopping the search, but one or both of the other members vote against it. When the collective search activity is coercively terminated, the subject unconditionally obtains the value drawn in the previous round.

The reservation value of collective search in the finite sequential search model is as follows:

$$R_t^{C3} = \underbrace{[1-(1-F(R_{t+1}^{C3}))^3]R_{t+1}^{C3}}_{\text{continuing collective search}} + \underbrace{[1-F(R_{t+1}^{C3})]^2 \int_{R_{t+1}^{C3}}^{3000} x dF(x)}_{\text{accepted by all members}}.$$

The first term on the right-hand side shows the value for the subject of continuing the collective search. $[1-(1-F(R_{t+1}^{C1}))^3]$ indicates the probability that at least one member votes against stopping the search. The second term represents the value for the subject of accepting a drawn offer when all the members vote to stop searching unanimously.

Using these value functions, in the next subsection, we illustrate numerical exercises to derive the difference in the reservation values between single-agent search and collective search and decompose the difference in the probability of stopping the search into the threshold and the vote aggregation effects .

4.4 Numerical exercise

We begin with comparisons of reservation values in the infinite sequential search model. Table 1 displays the reservation value and the probability of stopping the search for each type of search model.

The numerical exercise demonstrates that the reservation values are lower in any collective search model, regardless of the type of the plurality voting rules, than in the single-agent search model. This ensures that negative externalities caused by the collective decision to stop searching lower the reservation value. In this specific model where a subject has to accept a value drawn in the previous round when the search activity is coercively terminated with a probability of 0.05, these negative externalities decrease the reservation value most severely in the collective search model with the one-vote rule, followed by the collective search model with the unanimity rule, and then the model with the majority rule. In our experiments, we predict that the earliest round in which a subject votes to stop searching occurs in the collective search case with the one-vote rule.

In this specific setting that is slightly different from the original AAV model, a subject can receive at least the value drawn in the previous round when her or his search activity is terminated with a probability of 0.05. The loss that the subject would have incurred by continuing the search and then being coercively terminated is relatively small, thus implying that the effect of the negative externality whereby collective search continues even though the subject wants it to stop because the other members choose to continue searching, is relatively small. Comparatively speaking, the effect of the opposite negative externality, whereby collective search stops because other members choose to stop, even though the subject wants it to continue, is relatively large. Therefore, the reservation value is relatively high in collective search with the unanimity rule where the first externality is strongly involved. On the other hand, the reservation value is relatively low in collective search with the one-vote rule where the second externality is largely involved. Our numerical setting shows that the reservation value is highest in collective search with the majority rule in which both externalities are involved but only moderately rather than strongly .[7]

A higher reservation value does not necessarily imply a higher probability of stopping the search; that is, the probability of stopping the search depends not only on the reservation value of the group members, but also on the voting rule. According to Table 1, the probability of stopping the search is higher in collective search with the majority and one-vote rules than in single-agent search. This thereby shortens the average search duration in these collective search models. On the other hand, the probability of stopping the search is lower in collective search with the unanimity rule than in single-agent search, despite the fact that the reservation value is lower in the former

[7] In the AAV model with infinite sequential search, the discount factor is one of the most important factors determining the order of reservation values among the three plurality voting rules. The numerical exercise (not shown here) illustrates that when the discount factor is 0.95, the same order of magnitude is obtained; that is, the reservation value is lowest in collective search with the one-vote rule, followed by the unanimity rule, and the majority rule. When the discount factor is 0.99, the reservation value is lowest for the one-vote rule, followed by the unanimity rule, and then the majority rule . As the discount factor decreases, this order is reversed. An individual who discounts the future largely bears the heavy burden of the negative externality involved when collective search continues because the other members prefer it to continue, despite the subject's preference to stop. Therefore, the reservation value is low under the unanimity rule. On the other hand, because the effect of the other negative externality whereby collective search stops despite the subject's preference to continue is relatively small when the discount factor is large, the reservation value is then relatively high under the one-vote rule in which this negative externality is strongly involved.

than in the latter.

The difference in the probability of stopping the search between single-agent search and collective search is decomposed into the two effects explained in Section 2: the threshold effect and the vote aggregation effect . Table 2 displays the decomposition into the two effects. As confirmed in Table 1, the threshold effect lowers the reservation value and thereby raises the probability of stopping the search in the case of collective search. The vote aggregation effect operates to increase the probability of stopping the search in the case of collective search with the one-vote rule, but decreases the probability of stopping the search in the case of collective search with the other two rules. Under the majority and unanimity voting rules, it takes time for members to reach an agreement to stop searching, which lowers the probability of stopping the search. In collective search with the majority rule, the threshold effect is dominant over the vote aggregation effect, so the probability of stopping the search is higher. On the other hand, the vote aggregation effect exceeds the threshold effect under the unanimity rule, lowering the probability of stopping the search. We predict that the average search duration is shortest in the case of collective search with the one-vote rule, followed by collective search with the majority rule, then single-agent search, and, finally, collective search with the unanimity rule.

Our concern moves to the numerical solution in the finite sequential search model. Figure 5 depicts trends in the reservation value for various plurality voting rules. As one would expect, the reservation value is downward-sloping. An individual gradually concedes her or his own reservation value as the search round goes on. Similarly to the case of the infinite sequential search model with the death probability of 0.05, the reservation value of single-agent search is highest for any round, followed by collective search with the majority rule, the unanimity rule, and the one-vote rule. In our experiments, we predict that, as in the infinite case, the earliest round in which a subject votes to stop searching occurs in the collective search case with the one-vote rule, whereas the subject accepts a drawn value in the latest round in the single-agent search case.

4.5 Hypothesis

Following on from the numerical exercise, this subsection sets out experimental hypotheses to test the theoretical implications of the AAV model. We test two types of hypotheses relating to: (1) comparisons of search duration between single-agent search and collective search; and (2) comparisons of the willingness-to-stop searching between single-agent search and collective search.

The first hypothesis is described below.

- **H1:** The average search duration is shortest in the case of collective search with the one-vote rule, followed by collective search with the majority rule, then single-agent search, and, finally, collective search with the unanimity rule.

If this hypothesis is statistically supported, as indicated in the AAV model, the probability of stopping the search is higher in collective search with the one-vote and majority rules than in single-agent search, but the probability of stopping the search is lower in collective search with the unanimity rule than in single-agent search. H1 pays attention to the combined two effects (the threshold and the vote aggregation effects) on the average duration of collective search. The next step is to utilize the probit model to estimate determinants of the individual voting behavior regarding stopping searching, using data from each round-based decision from the eight games. This identifies the threshold effect whereby subjects are less picky in collective search than in single-agent search. We hypothesize as follows:

- **H2:** A subject is more likely to vote for stopping the search in an earlier round of collective search with the one-vote rule, followed, in order of likelihood, by collective search with the unanimity rule, then collective search with the majority rule, and, finally, single-agent search.

This test allows us to capture the threshold effect and compares the reservation values among the various plurality voting rules.

If we combine the estimated results from these two hypothetical tests of the search duration and the determinants of voting to stop searching, it is possible to identify another effect, albeit implicitly, called the vote aggregation effect.

4.6 Administration and payoffs

Three sessions for the finite sequential search model were conducted in the experimental laboratory of the Institute of Social and Economic Research at Osaka University on December 1, 2009. Each session differed in terms of the order of the games; the order of the first session was Games A, B-3, B-2, B-1, C-3, C-2, C-1, and A; the order of the second session was Games A, C-1, C-2, C-3, B-3, B-2, B-1, and A; and the order of the third session was Games A, B-1, B-2, B-3, C-1, C-2, C-3, and A. The order of the games was changed to control the anchoring effect, whereby search behavior in a game is affected by the previous games' results. The experiment involved a total of 63 undergraduate and graduate noneconomics-major students from Osaka University. The participants were seated at individual desks in each session.

Next, we conducted four sessions for the infinite sequential search model at the Center for Experimental Research in Social Sciences at Hokkaido University on February 2, 2010. The order of games in each session was as follows: first session: Games A, B-3, B-2, B-1, C-3, C-2, C-1, and A; second session: Games A, C-1, C-2, C-3, B-3, B-2, B-1, and A; third session: Games A, C-3, C-2, C-1, B-1, B-2, B-3, and A; and fourth session, Games A, B-1, B-2, B-3, C-1, C-2, C-3, and A. Subjects consisted of 60 undergraduate students from various academic disciplines. The experiments conducted in both universities were run entirely on computers using the software package *Z-Tree* (Fischbacher, 2007). [8]

The instruction sheet presented full information about the search task. After the experiment was done, the participants answered a questionnaire and then the payoff procedures took place. With regard to the payoff, we emphasized that: (i) the subjects' payoff was truncated at JPY0 (i.e., they could not incur losses from the search task) and (ii) they would earn an appearance fee of JPY1000. The performance pay was determined based on one of the results from the eight games randomly chosen by each subject. The expected total payoff was JPY2500 to 3000 in both universities; therefore, because the on-duty time for the experiment was approximately 90 minutes,

[8] The programs were produced by Takanori Kudou, a graduate student of the Engineering Division of Electrical, Electronic and Information Engineering, Osaka University.

the hourly wage was calculated at JPY1600 to 2000. This is approximately twice as much as the average hourly wage for college students.

5 Results

5.1 Search duration

We begin with a test of the first hypothesis (H1). Tables 3-1 and 4-1 display descriptive statistics, including average durations and their standard deviations, for the infinite and finite sequential search models. Table 3-1 shows that the average search duration for single-agent search is significantly longer in the last game than in the first game, implying that there may be an anchoring effect in the sense that a subject's search behavior is influenced by results she or he has already obtained in the previous experimental games. It is noted that there may be an identification bias in the statistical tests. In Table 4-1, it is clear, in contrast to Table 3-1, that the anchoring effect is minor because the difference in the search duration of single-agent search between the first game and the last game is statistically insignificant. According to both tables, the average search duration is longer in the case of collective search with the majority and unanimity rules when group members have different values (Game C) compared with when they have the same value (Game B), but the reverse is observed when the one-vote rule applies. As the required number of votes to stop searching increases, the average search duration is longer, regardless of whether the drawn value is the same or different among group members.

Tables 3-2 and 4-2 show comparative tests of the search duration between collective search with various plurality voting rules versus single-agent search. The upper three rows of these tables compare the average duration for single-agent search and collective search in which all group members draw the same value (Game B). According to the AAV model, if subjects are homogeneous with respect to their risk and loss attitudes, preferences, and other unobserved factors, there is no difference in the average duration between the two search models, regardless of which plurality voting rule applies. Both tables show that the null hypothesis of no difference in the average duration between the two search models is significantly rejected under any plurality voting rule, except for the unanimity rule in Table 3-2. Therefore, we can say that the subjects are not homogeneous with respect to their risk and loss attitudes, preferences, and unobserved factors. To correctly test the implications of the AAV model where members are homogeneous, it is necessary to control these differences that arise from heterogeneity among members.

The lower three rows of Tables 3-2 and 4-2 compare the average duration between single-agent search and collective search in which group members draw different values. Remember that the difference in the average duration between the two models arises from the heterogeneity among group members, as mentioned above, and also from uncertainty in terms of the values that other members draw. The search duration is shorter in collective search with the one-vote rule than in single-agent search at the 1% level of significance in both tables. Similarly, the search duration is longer in collective search with the unanimity rule than in single-agent search at the 1% level of significance. The search duration is shorter in collective search with the majority rule than in single-agent search at the 5% level of significance in Table 3-2, but insignificant in Table 4-2. So far, we have not identified whether the difference in the average duration arises from heterogeneity with respect to risk and loss attitudes, preferences, and other factors among group members or from uncertainty in the sense that no member knows what values other members hold. Thus, we can confirm the implications of the AAV model by deducting the differences displayed in the upper rows of Tables 3-2 and 4-2 from the differences displayed in the lower rows.[9]

Tables 3-3 and 4-3 show comparisons of the average duration between single-agent search and collective search, controlling for heterogeneity among group members. According to the first row of each table, the search duration is shorter in collective search with the one-vote rule than in single-agent search at the 1% level of significance. Similarly, the null hypothesis that the average duration in collective search with the unanimity rule is equal to or shorter than the average duration in single-agent search is rejected at the 1% level of significance. Another interpretation of this result is that as the number of group members increases from one to three, holding the unanimity rule

[9] We test the null hypothesis that the difference-in-difference, (Game C-1 - Game A) - (Game B-1 - Game A) = Game C-1 - Game B-1, is zero. The same procedure applies to the other two voting rules.

fixed, the average duration becomes longer. These results are consistent with the prediction of the AAV model. Looking at the comparisons between single-agent search and collective search with the majority rule in both tables, we cannot significantly reject any null hypothesis that the average duration differs. The AAV model predicts that if the reservation value of single-agent search (or the discount factor) is extremely low or extremely high, the average duration is shorter in collective search with the majority rule, but otherwise it is longer. It is not surprising that these outcomes are obtained from our experiment because, as shown in Table 1, the probability of stopping the search differs very little between collective search with the majority rule and single-agent search.

Tables 5 and 6 show estimated results of the determinants of search duration. Table 5 deals with the estimates of the infinite sequential search model, whereas Table 6 displays those of the finite sequential search model. The dependent variable is each subject's search duration in each game, while a vector of independent variables consists of treatment types, each subject's attitude toward risk, a female dummy, and/or individual dummies. The variables regarding risk attitude are included to control partially for individual heterogeneity. To collect these variables, we conducted a questionnaire for all participants after eight games and asked them three questions about their attitude toward risk. The first question was: "With at least what chance of rain do you take an umbrella?" Those who answered with a lower number were considered to be more risk averse. This number is referred to as representing risk aversion (I). The second question asked subjects what price they were willing to pay for a lottery with a 25% chance of winning JPY200 but a 75% chance of receiving JPY0. We then calculated the index measuring the extent of absolute risk aversion using Cramer et al. (2002).[10] Let this index denote risk aversion (II). If this index is positive, a subject is considered to be risk averse; if it is negative, the subject is considered to be risk prone. If the index is exactly zero, the subject is risk neutral. In a similar manner, we calculated an

[10] According to Cramer et al. (2002), the extent of absolute risk aversion is calculated as follows:

$$\frac{0.25 \times 200 - price}{0.5(0.25 \times 200^2 - 2 \times 0.25 \times 200 + price^2)},$$

where *price* implies the price that a subject is willing to pay for the lottery with a 25% chance of winning JPY200 but a 75% chance of receiving JPY0.

alternative index using the willingness-to-pay price for a lottery with a 25% chance of winning JPY2000 but a 75% chance of receiving JPY0. This index denotes risk aversion (III).

All columns of Tables 5 and 6 indicate the same result: the coefficient on Game C-1 is negative, whereas that on Game C-3 is positive, both at the 1% level of significance when the reference group is defined as the first trial of Game A. It is confirmed that the search duration is shorter in collective search with the one-vote rule, and longer in collective search with the unanimity rule. These results are consistent with the prediction of the AAV model. The coefficient on Game C-2, by contrast, is insignificant in both tables. As mentioned before, this result is not surprising because the AAV model shows that the search duration is either shorter or longer in collective search with the majority rule, depending mainly on the reservation value of the single-agent search model or the discount factor. The coefficient on the last trial of Game A, Game A(8), is positive at the 5% level of significance in Table 5. Subjects continue searching more aggressively in the last game than in the first game of single-agent search. This implies that the subjects change their search behavior through various experimental games and, that therefore, there is an anchoring effect. Because the coefficient on Game A(8) is insignificant in Table 6, there is no serious anchoring effect in the experiment for the finite sequential search model. The coefficient on risk aversion (I) is positive at the 5% level of significance in column [2] of Table 6, implying that the more risk prone subjects extend their search duration. The coefficients on other indices of risk aversion are insignificant.

5.2 The probability of voting to stop

This subsection considers each round-based decision on whether to vote for stopping the search and then tests the second hypothesis (H2). Tables 7 and 8 display estimates of the probit model of determinants of the vote to stop searching, using the round-based data of search decisions. The dependent variable is the dichotomous one indicating a value of one if a subject accepts a drawn value in the case of single-agent search or votes to stop searching in the case of a collective search activity; otherwise it takes a value of zero. The independent variables are dummies indicating treatments, the drawn value, the round, attitude toward risk, a female dummy, and/or individual dummies. The purpose of these estimates is to capture the difference in the reservation value between collective search and single-agent search or to extract the threshold effect quantitatively. Table 7 includes the estimates of the infinite sequential search model, whereas Table 8 deals with those of the finite sequential search model.

The two tables have the same results regarding the dummies indicating treatment types. In both tables, the coefficients on Game Bs (except Game B-1) and Game Cs are positive at the 1–5% level of significance, compared with the reference group of the first game of Game A, whereas the coefficient on Game B-1 is insignificant or marginally significant at the 10% level. Because the coefficients on Games B-2 and B-3 are significantly positive and different from zero, we can say that subjects are not homogeneous with respect to preferences among group members, and that there exists uncertainty in terms of other members' characteristics, which encourages subjects to vote in favor of stopping the search in an earlier round. Because the coefficients on collective search are positive when the group members draw different values (Game Cs), regardless of the plurality voting rule, the other uncertainty regarding what value other members draw from the distribution reinforces the incentive to vote to stop searching in an earlier round. These results confirm the threshold effect, which suggests that the reservation value is lower in collective search than in single-agent search in the AAV model.

Next, we focus on a comparison of the coefficients on Game Cs in terms of magnitude. The probability of voting to stop searching differs according to the plurality voting rules. In all columns except column [1] of Table 7, the coefficient is the largest for Game C-2, followed by Game C-1 and Game C-3. From these columns, we find that a subject is more likely to vote in favor of stopping the search in an earlier round under the majority rule, relative to the other two voting rules. The order of magnitude of the reservation values differs from that predicted by the numerical exercise displayed in Table 1. In our experiment, the reservation value is *lowest* in collective search with the majority rule, followed by the one-vote rule, and the unanimity rule. In contrast, the numerical exercise predicts that the reservation value will be *highest* in collective search with the majority rule, followed by the unanimity rule and the one-vote rule. One of the reasons for this result may be that the subject's preferences in relation to the two negative externalities (i.e., the externality relating to collective search stopping despite the subject's intention to continue, and the other externality whereby collective search continues despite the subject's intention to stop) are different from those assumed in the numerical exercise. Recall that the one-vote and unanimity rules are strongly influenced by the first and second externalities, respectively, whereas the majority rule is influenced by both externalities but only moderately. From the model used in the numerical analysis, we find that the reservation value is highest when the two negative externalities are involved moderately. However, subjects who actually participated in our experiment became more impatient to continue searching in an environment influenced moderately by the two negative externalities than they did in an environment where only one of the two negative externalities was strongly involved.

The order of the reservation values in Table 8 differs from that in Table 7. According to all columns of Table 8, the coefficient is largest for Game C-3, followed by Game C-2, then Game C-1. Subjects are more likely to accept a drawn value in the earliest round under the unanimity rule, followed by the majority and one-vote rules. It is notable that the order of the reservation values in terms of size for Games C-1 and C-3 is opposite to that found in the numerical illustration. This implies that, compared with the numerical exercise, each subject is more averse to incurring the disutility caused by the negative externality whereby collective search continues despite the subject's intention to stop than we would expect from the numerical exercise. It is confirmed that subjects who actually participated in the experiment do not want to keep searching but rather want to stop sooner. These findings are consistent with previous studies on search experiments. Schunk and Winter (2009) explored the reasons for this result.

The coefficient on "value" is positive at the 1% level of significance in all columns of both tables. When a subject draws a higher value, she or he is more likely to vote to accept it. In Table 8 dealing with the finite sequential search model, the variable of round has a positive effect on the probability of voting to stop searching at the 1% level of significance. As a subject moves on to a latter round, she or he is more likely to vote to stop searching because the search duration is finite in these sessions. However, according to column [2] of Table 7, which deals with the infinite sequential search model, the coefficient on round remains positive at the 1% level of significance. This refutes our expectation that the round does not affect a determinant of voting to stop searching in infinite sequential search. There are other interesting variables affecting the probability of voting to stop searching. In Table 7, the coefficient on female is insignificant, but it turns out to be positive at the 1% level of significance in Table 8. Female participants at Osaka University are more likely to stop searching earlier.

The variables indicating the extent of absolute risk aversion are as expected. The coefficients on risk aversion (II) and (III) are positive at the 1% level of significance in Table 7 and at the 5% level in Table 8, implying that more risk averse subjects are likely to vote to stop searching in an earlier round. The same result is confirmed using the index of risk aversion (I) in Table 8 because the sign of its coefficient is negative at the 5% level of significance.[11]

6 Concluding remarks

This paper designed laboratory experiments to study both finite and infinite collective search models and tested the implications obtained in Albrecht, Anderson, and Vroman (2010). To date, there have been no empirical studies on collective search because it is difficult to collect data. Throughout our laboratory experiment, we collected original data from subjects. This paper's main contributions are to provide experimental evidence about collective search and then to test the properties of the reservation values. Our experimental design involved decomposing the source of the difference in search behavior between single-agent search and collective search into effects caused by heterogeneity with respect to preferences across members and uncertainty in terms of the values other members draw from the identically independent distribution.

Our findings are summarized as follows. Controlling heterogeneity of preferences among group members, the average search duration is longer in collective search with the unanimity rule than

[11] Recall that risk aversion (I) measures at what chance of rain you bring your umbrella, with those who provided a lower number as their answer considered to be more risk averse.

in single-agent search, whereas the average search duration is shorter in collective search in which at least one vote is required to stop the search than in single-agent search in both the infinite and the finite sequential search models. These results support the implications of the AAV model. In a comparison of single-agent search versus collective search with the majority rule, the hypothesis of no difference in the search duration is not significantly rejected in either model. It is not surprising that this result is obtained because the numerical exercise illustrates that the difference is trivial.

To identify the threshold effect whereby negative externalities caused by collective search involving voting operate to lower a member's reservation value, we estimated the determinants of voting to stop searching. We found that subjects are more likely to vote to stop searching in collective search than in single-agent search in both the finite and the infinite models, and that the earliest round in which the subjects vote to stop searching occurs in the collective search case with the majority rule in the infinite sequential search model and in the collective search case with the unanimity rule in the finite sequential search model. These estimated results confirm the threshold effect, in the sense that agents are less picky in collective search than in single-agent search, as the AAV model indicated. However, our experimental outcome is different from the AAV model's prediction in terms of the size order of the reservation values. This difference is attributable to subjects' preferences regarding the two negative externalities. From the experiment of the finite sequential search model, we found that a subject who actually participated in the experiment is more averse to incurring disutility caused by the negative externality involving collective search continuing despite the subject's intention to stop than we would expected from the numerical exercise. This same attitude to search activity in the laboratory experiments by subjects has often been observed in other studies.

Overall, we obtain experimental outcomes that are consistent with the implications suggested by the AAV model in terms of comparisons of the search duration and the probability of voting to stop searching for collective versus single-agent search. However, the outcomes differ according to the different plurality voting rules in terms of comparisons of the probability of voting to stop searching in the collective search model.

7 Appendix: Instruction

7.1 Infinite sequential search games at Hokkaido University

Note: Following is the instruction for Session 4 at Hokkaido University. Other sessions differed from this session in terms of the order of the games.

Welcome to our experiment! In this experiment, you will be asked to play eight games. In each game, you will be asked to choose either to accept a value that is randomly selected from a uniform distribution with a lower bound of zero and an upper bound of 3000, or to refuse this value and move on to the next round to wait for a higher value. If you are willing to accept an offered value, you click on the "Y" displayed on the PC screen; if not, you click on the "N". You can continue to search as long as you want, but please remember that your search activity will be terminated coercively with a probability of 5%, in a case of which you automatically receive the value drawn in the one round just before the termination. Your score will be determined according to the values that you accept.

We would like you to play eight different games. The first game is as follows.

- Game A: In each round, the computer randomly selects a value from a uniform distribution with a lower bound of zero and an upper bound of 3000. You decide whether to accept the value drawn from this distribution. If you accept the value, then you finish your search and the value is your score. If you do not accept the value, you move on to the next round and observe another value newly drawn by the computer.

The next three games are as follows.

- Game B-1: You are grouped with two other participants. Grouping is done randomly by the computer, and no member knows who the other members are. In this treatment, you play a collective search activity with the other two members. In each round, the computer randomly selects a value for *all* three group members, including you, from a uniform distribution with a lower bound of zero and an upper bound of 3000. All three group members, including you, receive the same value. You independently decide whether to accept the drawn value. If you prefer to accept the value, you vote for stopping the search, but if you do not accept the value, you vote against stopping. This collective search activity is stopped only if at least one member of the group votes for stopping. Otherwise, your group moves on to the next round and observes another value newly drawn by the computer.

- Game B-2: The process of Game B-2 is similar to that of Game B-1 except for the plurality voting rule; that is, this collective search activity is stopped only if at least two-thirds of the members of the group vote for stopping.

- Game B-3: The process of Game B-3 is similar to that of Game B-1 except for the plurality voting rule; that is, this collective search activity is stopped only if all three members of the group vote for stopping.

The next three games are as follows:

- Game C-1: You are grouped with two other participants. Grouping is done randomly by the computer, and no member knows who the other members are. In this treatment, you play a collective search activity with the other two members. In each round, the computer randomly selects for *each* group member a value from a uniform distribution with a lower bound of zero and an upper bound of 3000. Each group member therefore has a different value, and you do not know what value the other two members draw, and vice versa. You decide whether to accept the drawn value. If you accept your value, you vote for stopping the search, but if you do not accept your value, you vote against stopping. This collective search activity is stopped only if at least one member of the group votes for stopping. Otherwise, your group moves on to the next round, and each member receives another value newly drawn by the computer.

- Game C-2: The process of Game C-2 is similar to that of Game C-1 except for the plurality voting rule; that is, this collective search activity is stopped only if at least two-thirds of the members of the group vote for stopping.

- Game C-3: The process of Game C-3 is similar to that of Game C-1 except for the plurality voting rule; that is, this collective search activity is stopped only if all three members of the group vote for stopping.

The final game is as follows.

- Game A: In each round, the computer randomly selects a value from a uniform distribution with a lower bound of zero and an upper bound of 3000. You decide whether to accept the value drawn from this distribution. If you accept the value, then you finish your search and the value is your score. If you do not accept the value, you move on to the next round and observe another value newly drawn by the computer.

Before starting the experiment, we would like you to practice Game A once. Please let us know if you have any questions. After the experiment, please respond to a questionnaire. You will be paid an appearance fee of JPY1000. The performance pay will be determined based on one of the scores from the eight games you randomly choose, and your payment will be calculated as JPY1 for each scoring point. Payment processes will take place after the experiment is concluded. Please be quiet and do not communicate with other participants during the experiment. Thank you for your participation.

7.2 Finite sequential search games at Osaka University

Note: Following is the instruction for Session 3 at Osaka University. Other sessions differed from this session in terms of the order of the games.

Welcome to our experiment! In this experiment, you will be asked to play eight games. In each game, subject to a maximum number of 20 rounds, you will be asked to choose either to accept a value that is randomly selected from a uniform distribution with a lower bound of zero and an upper bound of 3000 or to refuse this value and move on to the next round to wait for a higher value. If you are willing to accept an offered value, you click on the "Y" displayed on the PC screen; if not, you click on the "N". If you do not accept the value offered in the final round, your score will automatically be zero. Your score will be determined according to the values that you accept.

We would like you to play eight different games. The first game is as follows.

- Game A: In each round, the computer randomly selects a value from a uniform distribution with a lower bound of zero and an upper bound of 3000. You decide whether to accept the value drawn from this distribution. If you accept the value, then you finish your search and the value is your score. If you do not accept the value, you move on to the next round and observe another value newly drawn by the computer. You can continue to search for up to 20 rounds.

The next three games are as follows.

- Game B-1: You are grouped with two other participants. Grouping is done randomly by the computer, and no member knows who the other members are. In this treatment, you play a collective search activity with the other two members. In each round, the computer randomly selects a value for *all* three group members, including you, from a uniform distribution with a lower bound of zero and an upper bound of 3000. All group members, including you, receive the same value. You independently decide whether to accept the drawn value. If you accept the value, you vote for stopping the search, but if you do not accept the value, you vote against stopping. This collective search activity is stopped only if at least one member of the group votes for stopping. Otherwise, your group moves on to the next round and observes another value newly drawn by the computer. Your group can continue to search for up to 20 rounds.

- Game B-2: The process of Game B-2 is similar to that of Game B-1 except for the plurality voting rule; that is, this collective search activity is stopped only if at least two-thirds of the members of the group vote for stopping.

- Game B-3: The process of Game B-3 is similar to that of Game B-1 except for the plurality voting rule; that is, this collective search activity is stopped only if all three members of the group vote for stopping.

The next three games are as follows.

- Game C-1: You are grouped with two other participants. Grouping is done randomly by the computer, and no member knows who the other members are. In this treatment, you play a collective search activity with the other two members. In each round, the computer randomly selects a value for *each* group member from a uniform distribution with a lower bound of zero and an upper bound of 3000. Each group member therefore has a different value, and you do not know what the other two members draw, and vice versa. You decide whether to accept the drawn value. If you accept your value, you vote for stopping the search, but if you do not accept your value, you vote against stopping. This collective search activity is stopped only if at least one member of the group votes for stopping. Otherwise, your group moves on to the next round, and each member observes another value newly drawn by the computer. Your group can continue to search for up to 20 rounds.

- Game C-2: The process of Game C-2 is similar to that of Game C-1 except for the plurality voting rule; that is, this collective search activity is stopped only if at least two-thirds of members of the group vote for stopping.

- Game C-3: The process of Game C-3 is similar to that of Game C-1 except for the plurality voting rule; that is, this collective search activity is stopped only if all three members of the group vote for stopping.

The final game is as follows.

- Game A: In each round, the computer randomly selects a value from a uniform distribution with a lower bound of zero and an upper bound of 3000. You decide whether to accept the value drawn from this distribution. If you accept the value, then you finish your search and the value is your score. If you do not accept the value, you move on to the next round and observe another value newly drawn by the computer. You can continue to search for up to 20 rounds.

Before starting the experiment, we would like you to practice Game A once. Please let us know if you have any questions. After the experiment, please respond to a questionnaire. You will be paid an appearance fee of JPY1000. The performance pay will be determined based on one of the scores from the eight games you randomly choose, and your payment is calculated as JPY1 for each scoring point. Payment processes will take place after the experiment is concluded. Please be quiet and do not communicate with other participants during the experiment. Thank you for your participation.

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Table 1: Numerical Illustration of Reservation Values and Probability of Stopping the Search (Infinite Sequential Search Model with a Death Probability 5%)

	reservation value	probability of stopping the search	
Xs	2451.77	1- P(Xs, 1,1)	0.183
Xc1 (1/3)	1621.67	1- P(Xc1, 3, 1)	0.842
Xc2 (2/3)	1968.39	1- P(Xc2, 3, 2)	0.273
Xc3 (3/3)	1941.57	1- P(Xc3, 3, 3)	0.044

Xs represents the reservation value in single-agent search. Xc1, Xc2 and Xc3 represent the reservation value in collective serach with the one-vote rule, the majority rule and the unanimity rule, respectively. The model assumes that three agents play each collective activity.

Table 2: Numerical Illustration of Decomposition into the Threshold and Vote Aggregation Effects (Infinite Sequential Search Model with a Death Probability 5%)

Xs versus Xc1		Xs versus Xc2		Xs versus Xc3	
1- P(Xs, 3, 1)	0.454	1- P(Xs, 3, 2)	0.088	1 - P(Xs, 3, 3)	0.006
threshold effect	0.388		0.185		0.038
vote aggregation	0.271		-0.095		-0.177
total difference	0.659		0.091		-0.139

The threshold effect indicates (1-P(Xc, 3, i))-(1-P(Xs, 3, i) while the vote aggregation effect represents (1-P(Xs, 3, i))- (1-P(Xs, 1, 1) where i=1, 2, and 3. The total difference represents the sum of the two effects or (1-P(Xc, 3, i))-(1-(P(Xs, 1, 1)). The model assumes that three agents play each collective activity.

Table 3-1: Average Search Durations (Infinite Sequential Search)

	value	voting rule	#searchers	sample	mean	sd	max	min
Game A(1)			1	60	3.233	3.306	18	1
Game B-1	commom	one vote	3	60	2.650	1.571	6	1
Game B-2	commom	majority	3	60	2.750	1.684	6	1
Game B-3	commom	unanimity	3	60	3.600	2.981	13	1
Game C-1	different	one vote	3	60	1.300	0.561	3	1
Game C-2	different	majority	3	60	2.850	1.921	7	1
Game C-3	different	unanimity	3	60	11.700	8.947	32	1
Game A(8)			1	60	4.633	4.422	21	1
Average				60	4.090	4.992	32	1

Table 3-2: Comparisons with Single-Agent Search

Game B-1	common	one vote	The search duration is shorter at the 1% level of significance.
Game B-2	common	majority	The search duration is shorter at the 5% level of significance.
Game B-3	common	unanimity	The search duration is insignificantly shorter.
Game C-1	different	one vote	The search duration is shorter at the 1% level of significance.
Game C-2	different	majority	The search duration is shorter at the 5% level of significance.
Game C-3	different	unanimity	The search duration is longer at the 1% level of significance.

Table 3-3: Comparisons with Search Durations of Collective Search

Game B-1 vs Game C-1	The search duration is shorter in Game C-1 at the 1% level of significance.
Game B-2 vs Game C-2	The search duration is insignificantly longer in Game C-2.
Game B-3 vs Game C-3	The search duration is longer in Game C-3 at the 1% level of significance.

The experiment was conducted at Hokkaido University

Table 4-1: Average Search Durations (Finite Sequential Search)

	value	voting rule	#searchers	sample	mean	sd	max	min
Game A(1)			1	63	5.079	4.408	19	1
Game B-1	common	one vote	3	63	3.762	2.487	9	1
Game B-2	common	majority	3	63	3.952	3.553	12	1
Game B-3	common	unanimity	3	63	6.524	4.568	20	1
Game C-1	different	one vote	3	63	1.381	0.580	3	1
Game C-2	different	majority	3	63	4.476	3.026	12	1
Game C-3	different	unanimity	3	63	11.762	7.141	20	2
Game A(8)			1	63	5.984	5.253	20	1
Average				63	5.365	5.114	20	1

Table 4-2: Comparisons with Single-Agent Search

Game B-1	common	one vote	The search duration is shorter at the 1% level of significance.
Game B-2	common	majority	The search duration is shorter at the 5% level of significance.
Game B-3	common	unanimity	The search duration is longer at the 10% level of significance.
Game C-1	different	one vote	The search duration is shorter at the 1% level of significance.
Game C-2	different	majority	The search duration is insignificantly shorter.
Game C-3	different	unanimity	The search duration is longer at the 1% level of significance.

Table 4-3: Comparison with Search Durations of Collective Search

Game B-1 vs Game C-1	The search duration is shorter in Game C-1 at the 1% level of significance.
Game B-2 vs Game C-2	The search duration is insignificantly longer in Game C-2.
Game B-3 vs Game C-3	The search duration is longer in Game C-3 at the 1% level of significance.

The experiment was conducted at Osaka University.

Table 5: Estimations of Search Durations (Infinite Sequential Search)

Search duration	[1]		[2]		[3]		[4]		[5]	
Game B-1	-0.583		-0.610		-0.583		-0.583		-0.583	
	(0.518)		(0.475)		(0.471)		(0.472)		(0.473)	
Game B-2	-0.483		-0.542		-0.483		-0.483		-0.483	
	(0.515)		(0.478)		(0.479)		(0.478)		(0.479)	
Game B-3	0.367		0.373		0.367		0.367		0.367	
	(0.610)		(0.582)		(0.576)		(0.571)		(0.575)	
Game C-1	-1.933	***	-1.949	***	-1.933	***	-1.933	***	-1.933	***
	(0.492)		(0.433)		(0.431)		(0.431)		(0.433)	
Game C-2	-0.383		-0.424		-0.383		-0.383		-0.383	
	(0.534)		(0.494)		(0.494)		(0.490)		(0.494)	
Game C-3	8.467	***	8.525	***	8.467	***	8.467	***	8.467	***
	(1.140)		(1.243)		(1.230)		(1.233)		(1.233)	
Game A(8)	1.400	**	1.441	**	1.400	**	1.400	**	1.400	**
	(0.654)		(0.714)		(0.711)		(0.709)		(0.714)	
Risk aversion (I)			0.020							
			(0.013)							
Risk aversion (II)					25.236					
					(47.085)					
Risk aversion (III)							-471.217			
							(438.609)			
Female									0.028	
									(0.364)	
ID	YES		NO		NO		NO		NO	
N	480		472		480		480		480	
F-test	0.000		0.000		0.000		0.000		0.000	

Parentheses represent the robust standard errors. The dependent variable represents a subject's search durations. Game B-1 (common value + one-vote rule), Game B-2 (common value + majority rule), Game B-3 (common value + unanimity rule), Game C-1 (different values + one-vote rule), Game C-2 (different values + majority rule), Game C-3 (different values + unanimity rule). Game A(8) is the single-agent search game that subjects played in the last trial, which captures the anchoring effect, compared with the first trial of Game A (A(1)). The experiment was conducted at Hokkaido University.

Table 6: Estimations of Search Durations (Finite Sequential Search)

Search duration	[1]	[2]	[3]	[4]	[5]
Game B-1	-1.317 *	-1.226 *	-1.207 *	-1.207 *	-1.317 **
	(0.676)	(0.651)	(0.664)	(0.662)	(0.642)
Game B-2	-1.127	-1.210 *	-1.310 *	-1.310 *	-1.127
	(0.706)	(0.717)	(0.729)	(0.728)	(0.713)
Game B-3	1.444 *	1.435 *	1.500 *	1.500 *	1.444 *
	(0.759)	(0.810)	(0.848)	(0.847)	(0.802)
Game C-1	-3.698 ***	-3.661 ***	-3.672 ***	-3.672 ***	-3.698 ***
	(0.598)	(0.571)	(0.588)	(0.588)	(0.563)
Game C-2	-0.603	-0.629	-0.810	-0.810	-0.603
	(0.635)	(0.679)	(0.695)	(0.695)	(0.672)
Game C-3	6.683 ***	6.597 ***	6.534 ***	6.534 ***	6.683 ***
	(0.994)	(1.057)	(1.101)	(1.101)	(1.058)
Game A(8)	0.905	0.887	0.397	0.397	0.905
	(0.804)	(0.853)	(0.856)	(0.856)	(0.866)
Risk aversion (I)		0.025 **			
		(0.011)			
Risk aversion (II)			9.808		
			(42.234)		
Risk aversion (III)				-61.352	
				(543.734)	
Feamle					-0.323
					(0.381)
ID	YES	NO	NO	NO	NO
N	504	496	464	464	504
F-test	0.000	0.000	0.000	0.000	0.000

Parentheses represent the robust standard errors. The dependent variable represents a subject's search durations. Game B-1 (common value + one-vote rule), Game B-2 (common value + majority rule), Game B-3 (common value + unanimity rule), Game C-1 (different values + one-vote rule), Game C-2 (different values + majority rule), Game C-3 (different values + unanimity rule). Game A(8) is the single-agent search game that subjects played in the last trial, which captures the anchoring effect, compared with the first trial of Game A (A(1)). The experiment was conducted at Osaka University.

Table 7: Probit Estimation of the Determinants of Stopping the Search (Infinite Sequential Search)

Willing to accept=1	[1]		[2]		[3]		[4]		[5]		[6]	
	Coef.		Coef.		Coef.		Coef.		Coef.		Coef.	
Value	0.004	***	0.004	***	0.002	***	0.002	***	0.002	***	0.002	***
	(0.000)		(0.000)		(0.000)		(0.000)		(0.000)		(0.000)	
Round			0.048	***								
			(0.015)									
Game B-1	0.145		0.253		0.359		0.366	*	0.298		0.375	*
	(0.306)		(0.315)		(0.220)		(0.218)		(0.216)		(0.218)	
Game B-2	0.609	**	0.704	***	0.607	***	0.586	***	0.528	***	0.603	***
	(0.251)		(0.259)		(0.190)		(0.192)		(0.187)		(0.190)	
Game B-3	0.917	***	0.996	***	0.776	***	0.756	***	0.671	***	0.762	***
	(0.332)		(0.337)		(0.205)		(0.206)		(0.209)		(0.205)	
Game C-1	0.915	***	1.083	***	0.853	***	0.829	***	0.788	***	0.858	***
	(0.349)		(0.354)		(0.283)		(0.287)		(0.284)		(0.289)	
Game C-2	1.363	***	1.456	***	0.906	***	0.913	***	0.892	***	0.912	***
	(0.281)		(0.290)		(0.216)		(0.219)		(0.216)		(0.218)	
Game C-3	1.165	***	0.937	***	0.678	***	0.698	***	0.641	***	0.688	***
	(0.226)		(0.246)		(0.150)		(0.151)		(0.148)		(0.150)	
Game A(8)	-0.617	**	-0.637	**	-0.422	**	-0.458	**	-0.494	***	-0.425	**
	(0.288)		(0.299)		(0.179)		(0.182)		(0.179)		(0.179)	
Risk aversion (I)					-0.002							
					(0.003)							
Risk aversion (II)							35.380	***				
							(9.608)					
Risk aversion (III)									448.451	***		
									(108.92)			
Female											0.115	
											(0.091)	
ID	YES		YES		NO		NO		NO		NO	
N	1963		1963		1931		1963		1963		1963	
F Test	0.000		0.000		0.000		0.000		0.000		0.000	

Parentheses represent the standard errors. The dependent variable represents one if a subject chooses to stop searching, regardless of whether the search is actually ended. Game B-1 (common value + one-vote rule), Game B-2 (common value + majority rule), Game B-3 (common value + unanimity rule), Game C-1 (different values + one-vote rule), Game B-2 (different values + majority rule), Game C-3 (different values + unanimity rule). Game A(8) is the single-agent search game that subjects played in the last trial, which captures the anchoring effect, compared with the first trial of Game A (A(1)). The experiment was conducted at Hokkaido University.

Table 8: Probit Estimation of the Determinants of Stopping the Search (Finite Sequential Search)

Willing to accept=1	[1]		[2]		[3]		[4]		[5]	
	Coef.		Coef.		Coef.		Coef.		Coef.	
Value	0.003	***	0.002	***	0.002	***	0.002	***	0.002	***
	(0.000)		(0.000)		(0.000)		(0.000)		(0.000)	
Round	0.072	***	0.033	***	0.031	***	0.032	***	0.032	***
	(0.012)		(0.010)		(0.011)		(0.011)		(0.010)	
Game B-1	-0.148		-0.071		-0.075		-0.078		-0.011	
	(0.197)		(0.169)		(0.170)		(0.170)		(0.169)	
Game B-2	0.465	***	0.347	**	0.375	**	0.369	**	0.329	**
	(0.179)		(0.158)		(0.161)		(0.161)		(0.157)	
Game B-3	0.561	***	0.638	***	0.638	***	0.639	***	0.615	***
	(0.179)		(0.152)		(0.155)		(0.156)		(0.151)	
Game C-1	0.949	***	0.951	***	0.957	***	0.947	***	0.973	***
	(0.291)		(0.232)		(0.240)		(0.248)		(0.229)	
Game C-2	1.316	***	0.972	***	1.006	***	1.002	***	1.018	***
	(0.203)		(0.169)		(0.173)		(0.173)		(0.168)	
Game C-3	1.638	***	1.424	***	1.441	***	1.442	***	1.441	***
	(0.203)		(0.161)		(0.163)		(0.162)		(0.160)	
Game A(8)	-0.300	*	-0.199		-0.204		-0.212		-0.240	*
	(0.173)		(0.146)		(0.149)		(0.150)		(0.144)	
Risk aversion (I)			-0.005	**						
			(0.002)							
Risk aversion (II)					19.782	**				
					(9.998)					
Risk aversion (III)							277.443	**		
							(123.247)			
Female									0.223	***
									(0.084)	
ID	YES		NO		NO		NO		NO	
N	2680		2609		2405		2405		2680	
F-Test	0.000		0.000		0.000		0.000		0.000	

Parentheses represent the standard errors. The dependent variable represents one if a subject chooses to stop searching, regardless of whether the search is actually ended. Game B-1 (common value + one-vote rule), Game B-2 (common value + majority rule), Game B-3 (common value + unanimity rule), Game C-1 (different values + one-vote rule), Game B-2 (different values + majority rule), Game C-3 (different values + unanimity rule). Game A(8) is the single-agent search game in the last trial, which captures the anchoring effect, compared with the first trial of Game A (A(1)). The experiment was conducted at Osaka University.

Figure 1: The Probability of Stopping the Search by the plurality Voting Rule

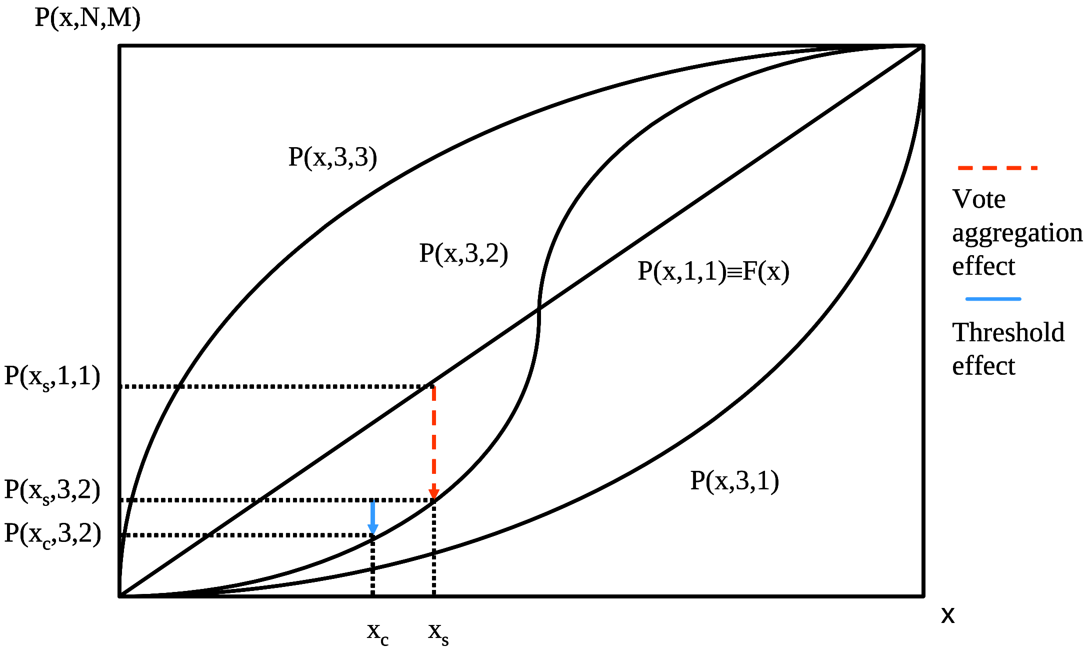


Figure 2: Threshold and Vote Aggregation Effects under the One-Vote Rule.

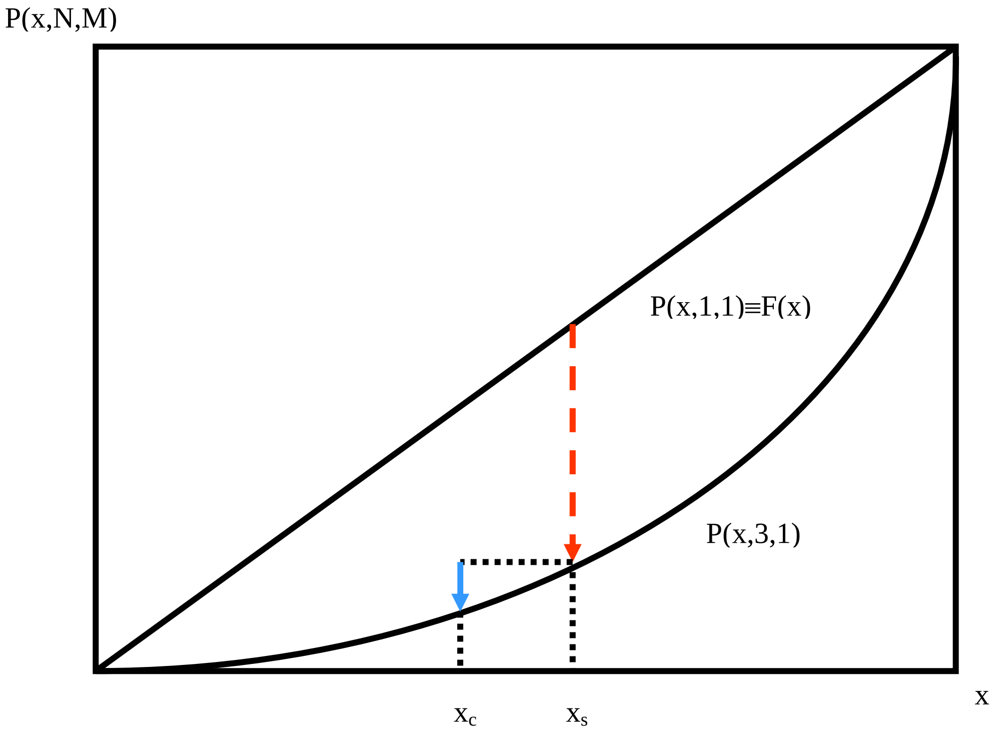


Figure 3: Threshold and Vote Aggregation Effects under the Unanimity Rule.

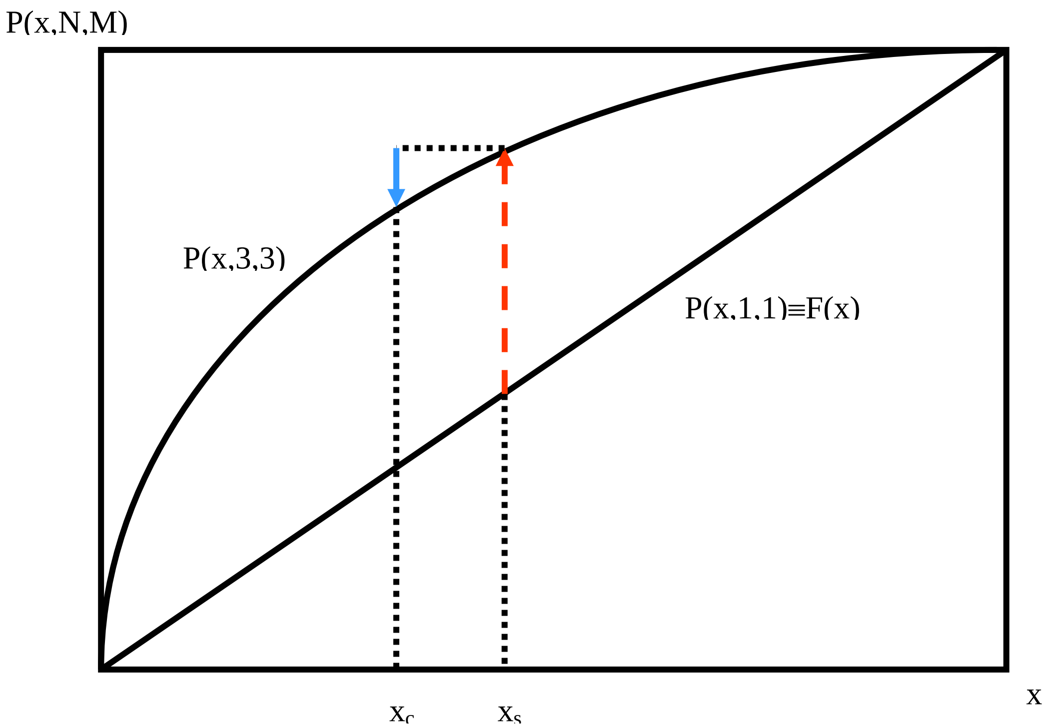


Figure 4: Threshold and Vote Aggregation Effects under the Majority Rule.

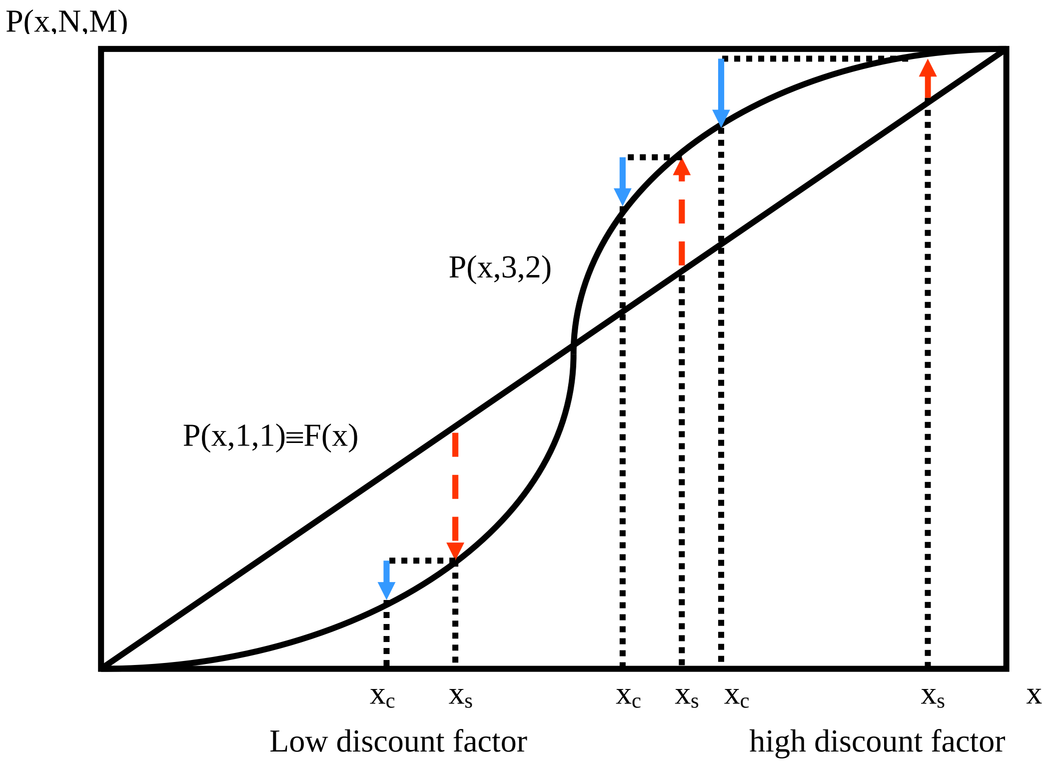
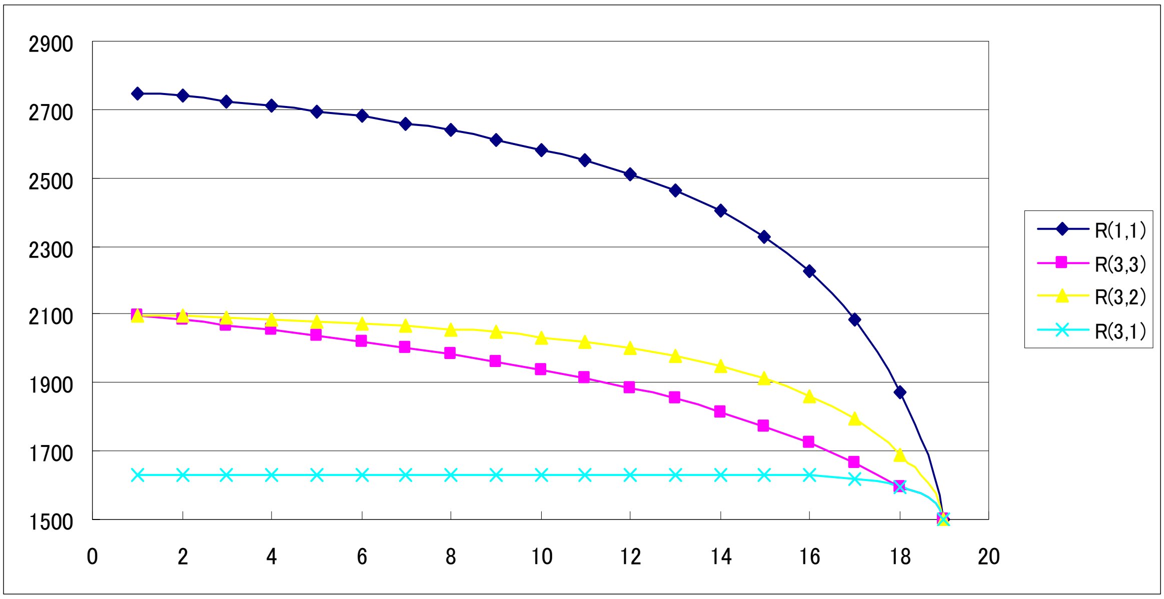


Figure 5: Trends in the Reservation Values in the Finite Sequential Search Model



R(,11): the reservation value in single-agent search

R(3,1): the reservation value in collective search with the one-vote rule

R(3,2): the reservation value in collective search with the majority rule

R(3,3): the reservation value in collective search with the unanimity rule