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A note on strategy-proofiness and single-plateaued preferences

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Abstract

This note integrates the role of Nash independence of irrelevant alternatives with the axioms of strategy-proofness and plateau-onliness to develop a recursive procedure over the number of agents for the construction of rules characterized as a class of admissible social choice functions in one pure public good economies with single-plateaued preferences.

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1 Introduction

We consider the provision of a pure public good and are interested in the construction of social choice functions that are *strategy-proof* and *plateau-only* when agents' preferences are *single-plateaued*— generalizing single-peakedness allowing for a segment of equally most-preferred alternatives, the *plateau.*[1] Building on Berga (1998) and Moulin (1984), we describe a recursive procedure for the construction of social choice functions of our interest that reduces to *tie-breaking rules*, one for each agent selecting a representative element from his plateau. We establish that any tie-breaking rule satisfying strategy-proofness, plateau-onliness, and *Nash independence of irrelevant alternatives* can be expressed as the projection of a strategy-proof and plateau-only social choice function defined over the remaining agents (Proposition 1). A drawback of the recursive procedure is that in each round we must suppose that the corresponding tie-breaking rules satisfy NIIA since this property is not always translated from one round to the next. In many allocation or voting problems, agents may have plateaus of equally most-preferred alternatives, such as desired tax rates, public good levels, or funding thresholds. Proposition 1 suggests that the selection of a representative point in each agent's plateau should not be arbitrary but should reflect the outcome guided by the preferences of others. This captures situations where agents consider the welfare or positions of their peers. For example, in public good provision or cost-sharing, individuals might favour compromise points that balance their own satisfaction with the concerns of their peers. Hereafter, Section 2 introduces the model and Section 3 presents the result and its proof.

2 Model

Let N be a **society** with n agents, $n \geq 2$, that must decide the provided level of a public good in $A = [0, 1]$, the set of **alternatives**.[2] Each agent $i \in N$ is equipped with an ordinal preference relation u_i over A.[3] The preference relation u_i is **single-plateaued** if there is an interval $\tau(u_i) \equiv [p^-(u_i), p^+(u_i)] \subseteq A$, called the plateau of u_i, such that for all $x_i, y_i \in A$, if $y_i < x_i \leq p^-(u_i)$ or $p^+(u_i) \leq x_i < y_i$, then $u_i(x_i) > u_i(y_i)$ and if $x_i, y_i \in \tau(u_i)$, then $u_i(x_i) = u_i(y_i)$. A preference relation u_i is **single-peaked** if it is single-plateaued and $p^-(u_i) = p^+(u_i)$. Denote by $\mathcal{F}$ the set of all single-plateaued preferences over A. Let $u = (u_1, ..., u_n) \in \mathcal{F}^n$ denote a **preference profile**, which can also be written as $u = (u_S, u_{N \setminus S})$ for $S \subseteq N$, and $\tau(u) = (\tau(u_1), ..., \tau(u_n)) \in A^n$ a **plateau profile**. A (n-agents) **social choice function** is a mapping $f : \mathcal{F}^n \to A$. It assigns the provided level of the public good for each preference profile. We consider social choice functions satisfying strategy-proofness, i.e., that prevent agents from gaining by misrepresenting their preferences.

1. Single-peaked preferences have been widely studied in the literature of social choice, political economy and public economics and a huge variety of results concerning strategy-proof rules have been obtained. See e.g. Black (1948), Moulin (1980), and Ching (1997), among many others. Many fewer results have considered single-plateaued preferences. See, e.g. Barberà (2007) for a paper about indifference; Ehlers (2000), Ehlers (2002) and Doghmi and Ziad (2015) for applications in allocation or private good settings; and Moulin (1984), Berga (1998) for public good economies. In the division problem, see e.g., Ching and Serizawa (1998), Massó and Neme (2001), and Sakai and Wakayama (2012) where single-plateaued is related to maximal domain results.
2. A similar result would be obtained if A was either $\mathbb{R}$ or any closed interval in $\mathbb{R}$.
3. For the sake of tractability, we use utility functions to denote them.

Strategy-proofness of f: For all $u \in \mathcal{F}^n$, all $i \in N$ and all $u'_i \in \mathcal{F}$, $u_i(f(u)) \geq u_i\left(f(u'_i, u_{N\setminus\{i\}})\right)$.
Another condition requires the outcome to only depend on the plateau profile.
Plateau-onliness of f: For any $i \in N$ and $u, u' \in \mathcal{F}^n$ such that for any $i \in N$, $\tau(u_i) = \tau(u'_i)$, then $f(u) = f(u')$.
We will apply these properties for societies $\bar{N} \subseteq N$.
According to Theorem 2 in Berga (1998), if we are interested in strategy-proof and plateau-only social choice functions, our attention should be restricted to *tie-breaking rules* that are themselves strategy-proof and plateau-only. Agent i's tie-breaking rule chooses a representative ballot in i's plateau, for each preference profile u:
A (n-agents) **tie-breaking rule for agent** $i \in N$ is a function $h_i : \mathcal{F}^n \to A$ such that $h_i(u) \in \tau(u_i)$ for all $u \in \mathcal{F}^n$.
Strategy-proofness of h_i, $i \in N$**:** For any $u \in \mathcal{F}^n$, any $j \in N \setminus \{i\}$ and any $u'_j \in \mathcal{F}$, $u_j(h_i(u)) \geq u_j\left(h_i\left(u'_j, u_{N\setminus\{j\}}\right)\right)$.
Plateau-onliness of h_i, $i \in N$**:** For any $u, u' \in \mathcal{F}^n$ such that for any $j \in N$, $\tau(u_j) = \tau(u'_j)$, then $h_i(u) = h_i(u')$.
Example 1 illustrates one *tie-breaking minmax social choice function*, the class characterized in Theorem 2 in Berga (1998). Let $(a_S)_{S\subseteq N}$ denote a list of parameters in A, one for each coalition $S \subseteq N$, satisfying the conditions in Equations 1 and 2, being A_f the range of f:

$$\forall S, T \subseteq N : S \subseteq T \Rightarrow a_T \leq a_S, \tag{1}$$

$$a_\emptyset = max\{x : x \in A_f\}, a_N = min\{x : x \in A_f\}. \tag{2}$$

Example 1 Let $N = \{1, 2\}$, $a_\emptyset = 1$, $a_N = 0$, and $a_{\{1\}} = a_{\{2\}} = \frac{1}{2}$. Define $h_i(u) = \frac{1}{2}(p^-(u_i) + p^+(u_i))$ for each $i = 1, 2$. The associated tie-breaking minmax social choice function f such that for any $u \in \mathcal{F}^2$,

$$f(u) = \min_{S\subseteq N}\left\{\max_{i\in S}(h_i(u), a_S)\right\}.$$

By Theorem 2 in Berga (1998), f is strategy-proof and plateau-only since each agent's tie-breaking rule satisfies both properties. □

We now relate (n-agents) tie-breaking rules to social choice functions for $(n-1)$ agents defined in Moulin (1984). Note that Moulin (1984) studies choice functions whose domain is a Cartesian product of the set of all single-plateaued profiles and the set of all closed subintervals of A, denoted as $\mathcal{I}$.[4] Thus, to carry out our analysis, notice first that each h_i, $i \in N$, can be viewed as $h_i : \mathcal{F}^{n-1} \times \mathcal{I} \to A$ such that for all $u_{N\setminus\{i\}} \in \mathcal{F}^{n-1}$, for all $B \in \mathcal{I}$, $h_i(u_{N\setminus\{i\}}, B) \in B$, where B represents $\tau(u_i)$ for some $u_i \in \mathcal{F}$. We use plateau-onliness to rewrite h_i in this way. Second, the tie-breaking rules must additionally satisfy *Nash Independence of Irrelevant Alternatives (NIIA)*.

Nash independence of irrelevant alternatives of h_i, $i \in N$**:** For all $u_{N\setminus\{i\}} \in \mathcal{F}^{n-1}$, $u_i, u'_i \in \mathcal{F}$ with $\tau(u'_i) \subseteq \tau(u_i)$ and $h_i(u_i, u_{N\setminus\{i\}}) \in \tau(u'_i)$, $h_i(u'_i, u_{N\setminus\{i\}}) = h_i(u_i, u_{N\setminus\{i\}})$.

Reducing i's plateau without excluding the chosen outcome does not alter the result. NIIA can be viewed as a *constancy*-type condition with respect to i's preferences. Example 2 illustrates NIIA and Example 3 shows it is not implied by strategy-proofness and plateau-onliness.

4. See Definition 1 and the note on p. 137 for the extension to single-plateaued preferences.

Example 2 For any $u \in \mathcal{F}^3$, let $p^- = \max\{p^-(u_1), p^-(u_2)\}$ and $p^+ = \min\{p^+(u_1), p^+(u_2)\}$. Define a (3-agents) tie-breaking rule as follows: $h_3(u) = proj_{\tau(u_3)}\Pi(u_1, u_2)$, where $\Pi(u_1, u_2) = p^-$ if $p^- > p^+$ and $\Pi(u_1, u_2) = \frac{1}{2}(p^- + p^+)$, otherwise. h_3 is plateau-only and NIIA (the former, since only the plateau profile matters when defining h_3; the latter, by Lemma 1 in Moulin (1984) since h_3 is a projection over $\tau(u_3)$). The proof of strategy-proofness is intuitive but case-based. As a hint, only agents without the outcome at the top may misrepresent, and for any profile at most one agent could try, but never profit. □

Example 3 For any $u \in \mathcal{F}^3$, $h_3(u) = \frac{1}{2}(p^-(u_3) + p^+(u_3))$. h_3 is strategy-proof since it does not depend on agents 1 and 2's preferences. h_3 is plateau-only since it depends only on his plateau. h_3 violates NIIA: take any $u_{N\backslash\{3\}}$, $\tau(u_3) = [0, \frac{7}{8}]$, and $\tau(u'_3) = [\frac{1}{4}, \frac{1}{2}]$. Then, $h_3(u) = \frac{7}{16} \in \tau(u'_3)$ but $h_3(u') = \frac{3}{8} \neq h_3(u) = \frac{7}{16}$. □

3 Recursive procedure

We first obtain that any strategy-proof and plateau-only tie-breaking rule of agent i satisfying NIIA can be written as the projection over i's plateau of the outcome of a strategy-proof and plateau-only social choice function over the remaining $(n-1)$ agents:

Proposition 1. *A tie-breaking rule $h_i : \mathcal{F}^n \to A$ for agent $i \in N$ is strategy-proof, plateau-only and satisfies NIIA if and only if for all $u_i \in \mathcal{F}$ and all $u_{N\backslash\{i\}} \in \mathcal{F}^{n-1}$, $h_i(u_i, u_{N\backslash\{i\}}) = proj_{\tau(u_i)}\Pi_i(u_{N\backslash\{i\}})$, where $\Pi_i : \mathcal{F}^{n-1} \to A$ is a strategy-proof and plateau-only social choice function.*

We need the following Lemma 1 in Moulin (1984) for single-plateaued preferences.

Lemma 1. *A tie-breaking rule $h_i : \mathcal{F}^n \longrightarrow A$ for agent $i \in N$ satisfies NIIA if and only if there exists a mapping $\Pi_i : \mathcal{F}^{n-1} \longrightarrow A$ for $i \in N$ such that for all $u_{N\backslash\{i\}} \in \mathcal{F}^{n-1}$ and $u_i \in \mathcal{F}$: $h_i(u_i, u_{N\backslash\{i\}}) = proj_{\tau(u_i)}\Pi_i(u_{N\backslash\{i\}})$.*[5]

Proof of Proposition 1 ($\Leftarrow$) ("if statement") Let Π_i be strategy-proof and plateau-only and $h_i(u_i, u_{N\backslash\{i\}}) = proj_{\tau(u_i)}\Pi_i(u_{N\backslash\{i\}})$. By Lemma 1, h_i satisfies NIIA. We prove strategy-proofness of h_i by contradiction. Suppose that there exist $u \in \mathcal{F}^n$, $j \in N\backslash\{i\}$, $v_j \in \mathcal{F}$, such that $u_j(h_i(v_j, u_{N\backslash\{j\}})) > u_j(h_i(u))$. Clearly, $h_i(u) \notin \tau(u_j)$. Without loss of generality, suppose that $h_i(u) < h_i(v_j, u_{N\backslash\{j\}})$. By definition of h_i, $\Pi_i(u_{N\backslash\{i\}}) \leq h_i(u)$ and $\Pi_i(v_j, u_{N\backslash\{i,j\}}) \geq h_i(v_j, u_{N\backslash\{j\}})$. By strategy-proofness of Π_i, $\Pi_i(v_j, u_{N\backslash\{i,j\}}) \geq r_{u_j}(\Pi_i(u_{N\backslash\{i\}}))$.[6] Note that for any $\omega_j \in \mathcal{S}$ with $p(\omega_j) = p^+(u_j)$, $\Pi_i(w_j, u_{N\backslash\{i,j\}}) = \Pi_i(u_{N\backslash\{i\}})$ by strategy-proofness and plateau-onliness of Π_i. Take w_j, which exists, such that $w_j\left(\Pi_i(v_j, u_{N\backslash\{i,j\}})\right) > w_j\left(\Pi_i(w_j, u_{N\backslash\{i,j\}})\right)$. This contradicts strategy-proofness of Π_i. Plateau-onliness of h_i is straightforward since h_i is the projection on agent i's plateau of Π_i, which is plateau-only itself. Otherwise, if for some preference profiles $u, u' \in \mathcal{F}^n$ such that for each $j \in N$, $\tau(u_j) = \tau(u'_j)$, $h_i(u) \neq h_i(u')$ holds, then $\Pi_i(u_{N\backslash\{i\}}) \neq \Pi_i(u'_{N\backslash\{i\}})$ since $\tau(u_i) = \tau(u'_i)$, which contradicts plateau-onliness of Π_i.

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5. The proof is straightforward from Moulin (1984)'s proof for single-peakedness, as he observes. Tie-breaking rules must also satisfy a technical condition, *continuity with respect to closed subintervals in* A. Formally, $h_i(u_i, u_{N\backslash\{i\}})$ is continuous with respect to $\tau(u_i) \in \mathcal{I}$. To define continuity, the set $\mathcal{I}$ is identified with $\mathbb{R}^2$ and endowed with the induced topology.

6. For $v \in \mathcal{F}$ and $a \in A\backslash\tau(v)$, $r_v(a) \equiv \{x \in A\backslash\{a\} : v(x) = v(a)\}$ if it exists, 1 if it does not exist and $a < p^-(v)$, and 0, otherwise.

($\Rightarrow$) ("only if"). Let h_i be a strategy-proof and plateau-only tie-breaking rule satisfying NIIA. By Lemma 1, for any $u_{N\backslash\{i\}} \in \mathcal{F}^{n-1}$, $u_i \in \mathcal{F}$, $h_i(u) = proj_{\tau(u_i)}\Pi_i(u_{N\backslash\{i\}})$ where $\Pi_i : \mathcal{F}^{n-1} \longrightarrow A$. It remains to prove that Π_i satisfies strategy-proofness and plateau-onliness as a social choice function on $\mathcal{F}^{n-1}$. We prove strategy-proofness of Π_i by contradiction. That is, suppose that there exists $j \in N\backslash\{i\}$, $u_{N\backslash\{i,j\}} \in \mathcal{F}^{n-2}$, $v_j \in \mathcal{F}$, such that $u_j\left(\Pi_i(v_j, u_{N\backslash\{i,j\}})\right) > u_j\left(\Pi_i(u_{N\backslash\{i\}})\right)$. Let $u_i \in \mathcal{F}$ such that $\tau(u_i) = A$. By definition, $h_i\left(u_i, v_j, u_{N\backslash\{i,j\}}\right) = \Pi_i(v_j, u_{N\backslash\{i,j\}})$ and $h_i(u) = \Pi_i(u_{N\backslash\{i\}})$. Then h_i would not be strategy-proof since $u_j(h_i(v_j, u_{N\backslash\{j\}}) > u_j(h_i(u))$.
Plateau-onliness of Π_i is straightforward since h_i is also plateau-only. Otherwise, if for some preference profiles $u_{N\backslash\{i\}}, u'_{N\backslash\{i\}} \in \mathcal{F}^{n-1}$ such that for each $j \in N \setminus \{i\}$, $\tau(u_j) = \tau(u'_j)$, $\Pi_i(u_{N\backslash\{i\}}) \neq \Pi_i(u'_{N\backslash\{i\}})$ holds, then $h_i(u) \neq h_i(u')$ since $\tau(u_i) = \tau(u'_i)$, which contradicts plateau-onliness of Π_i. ■

We now turn to social choice functions and describe a recursive procedure to construct the subclass of interest: those satisfying plateau-onliness and strategy-proofness. We start with $n = 2$ where the recursive device consists of one round with 3 steps and we are interested in any strategy-proof, plateau-only f on $\mathcal{F}^2$:

Step (1): By Theorem 2 in Berga (1998): there exist a strategy-proof and plateau-only tie-breaking rule for each agent and a set of parameters in A, $\{a_S\}_{S\subseteq N}$, such that for any $u \in \mathcal{F}^2$,

$$f(u) = \min_{S\subseteq N}\left\{\max_{i\in S}\{h_i(u), a_S\}\right\}.$$

By continuity on closed subintervals of A and NIIA, we obtain:
Step (2): By Proposition 1, $h_1(u) = proj_{\tau(u_1)}\Pi_1(u_2)$ and $h_2(u) = proj_{\tau(u_2)}\Pi_2(u_1)$ where both $\Pi_1 : \mathcal{F} \to A$ and $\Pi_2 : \mathcal{F} \to A$ are strategy-proof and plateau-only social choice functions on $\mathcal{F}$.

At this point, we need to characterize the class of 1-agent strategy-proof and plateau-only social choice functions, that are *minmax rules* as stated in Proposition 2.[7]

Proposition 2. *A social choice function $f : \mathcal{F} \to A$ is strategy-proof and plateau-only if and only if f is a median voter rule; that is, for all $u \in \mathcal{F}$, $f(u) = med\{c_\emptyset, c_1, g_1(u)\}$, where $c_\emptyset, c_1 \in A$, $c_1 \leq c_\emptyset$, and a plateau-only $g_1 : \mathcal{F} \to A$ such that $g_1(u) \in \tau(u)$.*

Step (3): By Proposition 2, Π_1 and Π_2 are median voter rules such that $\Pi_1(u_2) = med\{b^1_\emptyset, b^1_2, g_1(u_2)\}$ and $\Pi_2(u_1) = med\{b^2_\emptyset, b^2_1, g_2(u_1)\}$ for some given collections of parameters $(b^1_S)_{S\subseteq\{2\}} \in A$ and $(b^2_S)_{S\subseteq\{1\}} \in A$ satisfying conditions in Equations 1 and 2.

Adding up the information from the steps, we obtain that the shape of any strategy-proof and plateau-only 2-agents social choice function is a combination of minmax rules.

We can generalize this recursive argument for any number of agents n which would consist of $(n-1)$ rounds repeating steps 1 and 2, and apply step 3 once. We start by considering a social choice function with n agents in round 1 and in each round $l > 1$ studying social choice function with $[n-(l-1)]$-agents defined in previous rounds. In each round, besides

7. The proof of Proposition 2 follows from that of Theorem 2 in Berga (1998) for $n = 1$. Thus, we have that for all $u \in \mathcal{F}$, $f(u) = \min_{S\in\{\emptyset,\{1\}\}}\left\{\max_{i\in S}\{g_i(u), a_S\}\right\}$. Moreover, it is easy to prove the equivalent median expression where $b_S = a_S$ (see Moulin (1980) and Ching (1997) for single-peaked preferences and the equivalence between minmax rules and median voters for n agents).

assuming continuity, we require the tie-breaking rules to satisfy NIIA—a property not generally preserved across rounds (see Footnote 10, Example 4).
Summarizing, using Theorem 2 in Berga (1998) joint with our Propositions 1, 2 and the recursive argument on the number of agents, we can build a strategy-proof, plateau-only social choice function f for any number of agents. We do not know what additional condition(s) on f would guarantee that tie-breaking rules inherit NIIA, which remains a drawback of our approach. We hope our analysis serves as a catalyst for new perspectives leading to a fully closed characterization.

Example 4 presents a 3-agents social choice function exemplifying the recursive procedure and spelling out the tie-breaking and the associated two- and one-agent functions.

Example 4 Define for any $u \in \mathcal{F}^3$, $f(u) = median\{h_1(u), h_2(u), h_3(u)\}$, where $h_i(u) = p^-(u_i)$, for $i = 1, 2$ and $h_3(u) = proj_{\tau(u_3)}\Pi_3^1(u_1, u_2)$, being $\Pi_3^1 : \mathcal{F}^2 \to A$ strategy-proof and plateau-only.[8] By Theorem 2 in Berga (1998), f is strategy-proof and plateau-only. Observe that each tie-breaking rule is NIIA by Lemma 1, since $h_i(u) = proj_{\tau(u_i)}\Pi_i^1(u_{N\setminus\{i\}})$ where $\Pi_i^1(u_{N\setminus\{i\}}) = 0$, for $i \in \{1, 2\}$. So far, this corresponds to the first round in the recursive procedure—the initial application of step 1 (f being a minmax rule; a median rule in this example) and step 2 (each agent i's tie-breaking rule h_i being a projection over $\tau(u_i)$ of a strategy-proof and plateau-only rule Π_i^1 depending on the other two agents' preferences; Π_1^1 and Π_2^1 being constant rules). We start the second round for Π_3^1. By Theorem 2 in Berga (1998), Π_3^1 (known to be strategy-proof and plateau-only) must be a minmax rule which we assume to be as follows:[9] $\Pi_3^1(\bar{u}) = med\{\bar{h}_1(\bar{u}), \bar{h}_2(\bar{u}), \frac{1}{2}\}$ where $\bar{h}_1(\bar{u}) = proj_{\tau(u_1)}\Pi_1^2(u_2)$ and $\bar{h}_2(\bar{u}) = proj_{\tau(u_2)}\Pi_2^2(u_1)$ for any $\bar{u} \in \mathcal{F}^2$ by Proposition 1. Thus, we would have gone through the second round of the recursive procedure: second time applying steps 1 and 2. Now, step 3 applies, $\Pi_i^2 : \mathcal{F} \to A$ any strategy-proof and plateau-only as in Proposition 2 for $i = 1, 2$.[10] Suppose that Π_1^2 and Π_2^2 are such that $\Pi_1^2(u_2) = med\{0, 1, p^+(u_2)\} = p^+(u_2)$ and $\Pi_2^2(u_1) = med\{0, 1, p^+(u_1)\} = p^+(u_1)$. □

8. Note that f is a minmax rule satisfying Equations 1 and 2 where $a_S = a'_S$ for $\#S = \#S'$, $a_0 = a_1 = 1$, and $a_3 = a_2 = 0$.

9. That is, $\Pi_3^1(\bar{u}) = \min_{S \subseteq \{1,2\}} \left\{\max_{i \in S}\left\{\bar{h}_i(\bar{u}), b_S\right\}\right\}$ for any $\bar{u} \in \mathcal{F}^2$, where $b_S = b'_S$ for $\#S = \#S'$ and $b_0 = 1$, $b_2 = \frac{1}{2}$, $b_3 = 0$ and $\bar{h}_i$ being strategy-proof, plateau-only, and NIIA.

10. If $\bar{h}_i(\bar{u}) = \frac{1}{2}(p^-(\bar{u}_i) + p^+(\bar{u}_i))$ for some $i = 1, 2$, $\bar{h}_i$ would not satisfy NIIA (see Example 3).

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