System-Wide Error Attribution in Multi-Vehicle Operations: Theoretical Explanation, Implications, and Applications

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Introduction

In multi-vehicle aerial operation contexts, a single or several human operators (m) are responsible for managing multiple uncrewed vehicles (N). This is referred to as the m:N operational paradigm. (Aubuchon et. al., 2022)

When automation error occurs during m:N operations, especially if multiple vehicles exhibit automation error, a question is raised: **What level of system globality will the error be attributed to**? Globality refers to the levels within the conceptual hierarchy of a perceptual object.

Significant costs could be incurred if the error is falsely attributed to a higher globality level than it should be (e.g., multiple groups of vehicles as opposed to a single vehicle), and those vehicles are subsequently subject to grounding and evaluation/maintenance. Likewise, it could be problematic if error is falsely attributed to a component (i.e., a lower globality level), resulting in ongoing, unsafe operation of vehicles that should be grounded or evaluated.

Thus, to meet required safety standards and facilitate commercial viability, **multi-vehicle operators must be capable of appropriately attributing the level of globality of automation error within the system they are responsible for**.

Theoretical Framework

Gestalt Principles

- Originally confined to the domain of visual perception, but expanded to other sensory modalities, they describe how perceptual input is organized. (Todorovic, 2007; Wertheimer, 1938)
- When elements of a stimulus exhibit Gestalt Principles, it can result in perception of conceptual entities of a higher order (a whole) than the elements themselves (a part).
- Examples: Proximity, Common Fate, Similarity

Emergent Features

- Perceptual features that are possessed by wholes (collections or groups of parts; i.e., individual elements or components). (Wagemans et al., 2012)
- Wholes can exhibit a varying number of Gestalt Principles depending on how many Emergent Features they have.
- Examples: Parallelism, Collinearity, Symmetry

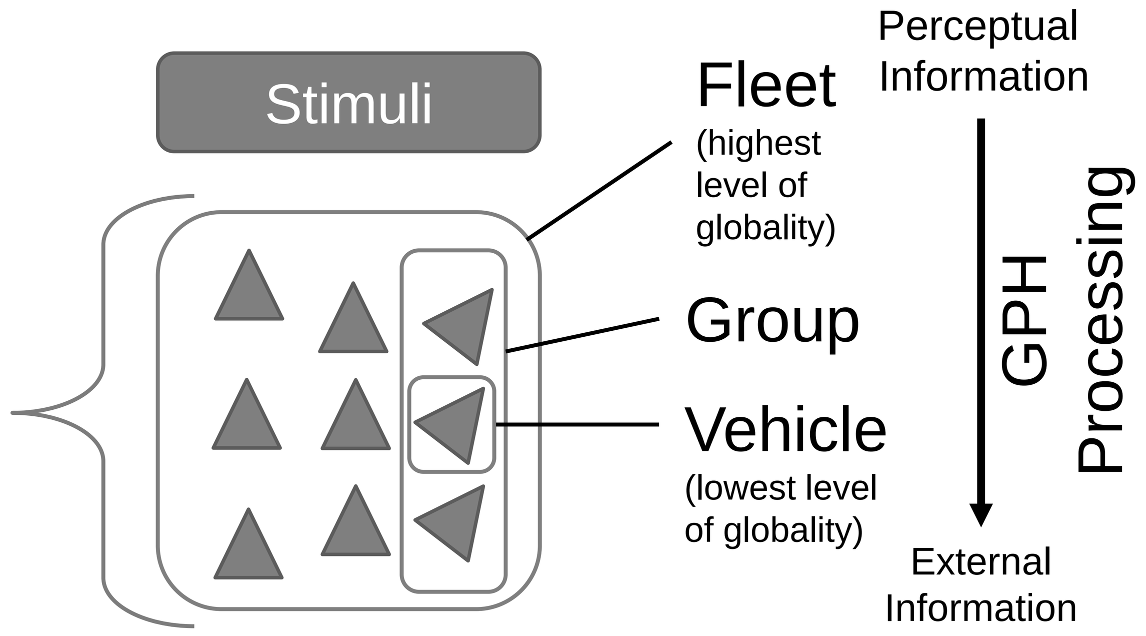
Global Precedence Hypothesis (GPH)

- In the context of sensory processing, the Global Precedence Hypothesis states that processing is, by default, at the level of global structures before proceeding towards analysis of local properties. (Navon, 1977)

External Information as Expertise

- Operators with higher expertise may have an improved capability to localize their attribution of error compared to novices.
- Information external to stimuli and at the cognitive disposal of operators could explain this improved capability. (Bean et al., 2011)

Emergent Features of **Stimuli** instantiate **Gestalt Principles** which drive novice operator's error attribution according to the **Global Precedence Hypothesis**

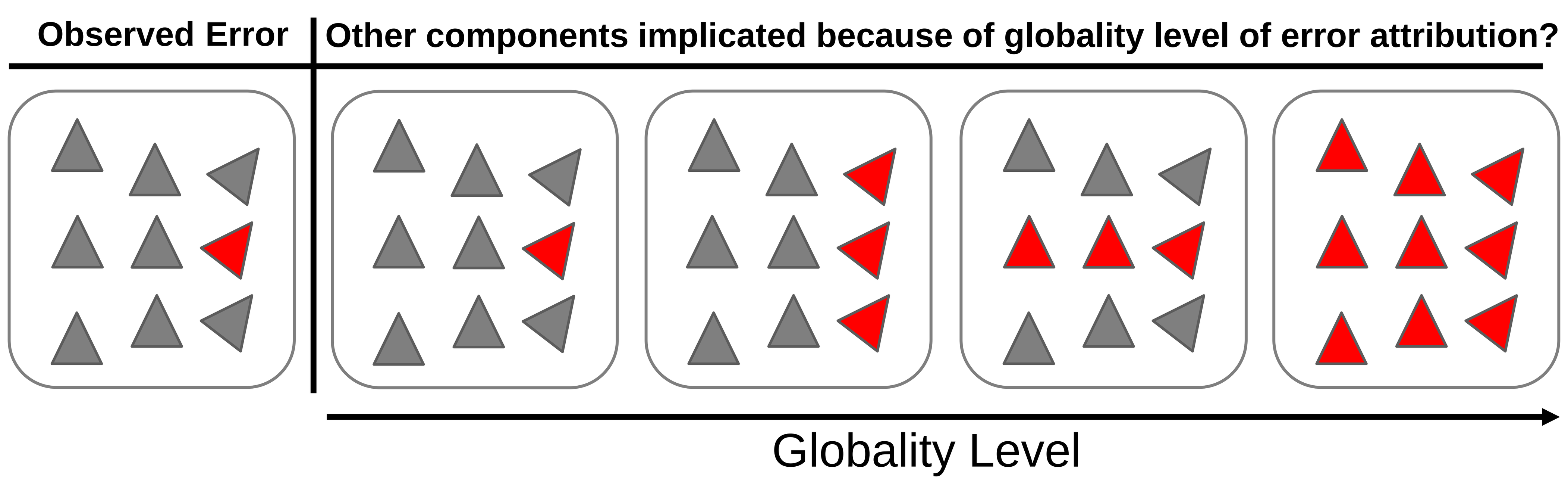


Implications for Manifestation of Contagion Effects

Contagion Effects (Pull-Down Effects)

When an operator thinks about, or treats, system components other than the erring component as though these components also erred because of their system-wide (global level) trust in the system. (Rice & Geels, 2010)

- It is possible that an operator, given both the perceptual and (perhaps, a lack of) external information they have, attributes local error to a higher level of system globality.
- If this occurs, it could result in the treatment of other non-erring components *as though* they also exhibited error.
- This would be due to non-erring components being falsely implicated given their conceptual relationship to the component/s exhibiting error



Role of Information Theory

Information Theory could serve as a mathematical framing of automation error attribution

$$H(a) = I(s, a) + Q(a|s)$$

- $H(a)$: Total amount of information needed to select an action or response over its alternatives
- $I(s, a)$: Sensorimotor control; raw perceptual information gleaned from stimuli
- $Q(a|s)$: Cognitive control; information provided by cognition external to stimuli

(Koechlin & Summerfield, 2007)

If an operator is relying purely on raw perceptual information to attribute error, then Q(a|s) = 0 and I(s, a) = H(a). The implication here is the operator is determining their response solely from a stimulus; this would be the case for a truly novice operator (in an idealized case). If the operator has an, at least partially accurate, mental model, which would be the construct that provides the information required to exert cognitive control over the raw perceptual information, then Q(a|s) > 0.

Discussion

This framework leverages existing theory yet offers additional explanation regarding mechanisms that moderate the manifestation of contagion effects, whilst maintaining coherence with precedent research. Examples include:

- Lyons et al. (2024) found that for expert users in a higher-fidelity, automation-aided task, a Pull-Down/Contagion Effect was not observed.
- Bean et al. (2011) found evidence for an operator's ability to employ a component-specific trust strategy when provided component-specific reliability information (even in the presence of salient emergent features).

Future Directions

- Testing theoretical framework via human subjects experiment
- Research questions to explore:
  1. Do novice operators tend to attribute errors to a level of system globality corresponding to the level of globality of Emergent Features of vehicles exhibiting error?
  2. Can emergent features of the errors themselves (in the case of multiple errors) matter?
  3. How does the provision of additional information about the system impact operator error attribution?

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