How complex signaling networks shape highly-coordinated, multistep cellular responses is poorly understood. Here, we made use of a network-perturbation approach to investigate causal influences, or “cross-talk,” among signaling modules involved in the cytoskeletal response of neutrophils to chemoattractant. We quantified the intensity and polarity of cytoskeletal marker proteins over time to characterize stereotyped cellular responses. Analyzing the effects of network disruptions revealed that not only does cross-talk evolve rapidly during polarization but also intensity and polarity responses are influenced by different patterns of cross-talk. Interestingly, persistent cross-talk is arranged in a surprisingly simple circuit: a linear cascade from front to back to microtubules influences intensities, and a feed-forward network in the reverse direction influences polarity. Our approach provided a rational strategy for decomposing a complex, dynamically evolving, signaling system and revealed evolving paths of causal influence that shape the neutrophil polarization response.